Design and development of high-temperature sensor using FBG

M. Venkata Reddy*, K. Srimannarayana, T.V. Apparao, M. Sai Shankar
Department of Physics, National Institute of Technology, Warangal-506004, India

ABSTRACT

A novel sensor for high-temperature measurement using Fiber Bragg grating (FBG) has been designed and simulated. The sensor works based on measurement of the shift in Bragg wavelength that corresponds to the temperature induced strain by making use of a mechanical transducer. The transducing element provides temperature dependent strain on FBG by means of differential linear thermal expansion of two different ceramic materials: Alumina and Silicon Carbide. The designed sensor can measure the temperatures from 20°C to 1500°C.

Keywords: High-temperature sensor, temperature measurement, FBG sensor, fiber optic sensor, temperature transducer

1. INTRODUCTION

Temperature measurement encompasses a wide variety of needs and applications in today's scientific and industrial environments. To meet these requirements, there is a necessity to develop a large number of sensors and devices [1]. The commercially available temperature sensors are classified into electrical and optical sensors. Besides these bulk electronics and optics based sensors, a variety of temperature sensors using fiber optics technology have also been developed [2]. The fiber optic sensors are typically small in size, highly sensitive, fast in response, immune to electromagnetic interference, resistant to harsh environments and have the capability of distributed sensing. Among them, fiber Bragg gratings (FBGs) constructed in a small segment of optical fiber are the most attractive sensing elements, owing to their enhanced sensitivity, accuracy and multiplexing capability [3,4].

As reported in the literature, over the past three decades, lot of research has been done in the field of FBG-based low-temperature sensing but the area of high-temperature sensing remains relatively unexplored [5]. And it is currently a topic that has attracted considerable interest from the sensor community because of its applications in important fields such as nuclear reactors, hydroelectric turbines, combustors, health-monitoring systems of aerospace engine, oil and gas industry, and high voltage transformers [6,7]. The standard Type-I gratings induced by weak and strong excimer laser, survive up to 450 °C and 700 °C respectively; beyond the limit the gratings get erased if they are directly subjected to the temperature [5,8,9]. However, femtosecond infrared (Fs-IR) laser induced Type-II gratings and regenerated gratings have been proved to withstand higher-temperature [10,11], but are limited by short term stability at high temperature [8,12-14]. Hence, there is a necessity to develop an alternative technique which enables high-temperature measurement using FBG sensors [15].

In this article we describe a novel design of an FBG-based sensor to measure the temperatures of up to 1500 °C.

2. THEORY

2.1. FBG sensor

FBG consists of periodically modulated refractive index zones in the fiber core. This grating structure results in reflection of light at a specific narrowband of wavelength, called Bragg wavelength and is expressed as $\lambda_B = 2n_{eff}\Lambda$ where, n_{eff} is the effective index of refraction of the fiber grating, and Λ is the grating period. Even a minute change in the periodic structure due to external perturbations such as strain, temperature will cause appreciable shift in Bragg wavelength [16]. The shift in Bragg wavelength, λ_B of FBG corresponding to both the parameters: strain and temperature is given as [3]

$$\Delta\lambda_B = \lambda_B[(\alpha_f + \xi_f)\Delta T + (1 - p_e)\varepsilon] \quad (1)$$

* vrmamidi@nitw.ac.in; Phone +91-870-2462592; www.nitw.ac.in

Photonic Fiber and Crystal Devices: Advances in Materials and Innovations in Device Applications IX,
edited by Shizhuo Yin, Ruyan Guo, Proc. of SPIE Vol. 9586, 95860I · © 2015 SPIE
CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2188215

where ΔT is the change in temperature, $\alpha_f = (1/\Lambda)(\partial\Lambda/\partial T)$ represents the thermal expansion coefficient of the fiber, $\xi_f = (1/n_{eff})(\partial n_{eff}/\partial T)$ represents the thermo-optic coefficient, ε is the axial strain applied on FBG, and p_e is an effective strain-optic constant.

The proposed FBG temperature sensor works based on measurement of the shift in Bragg wavelength that corresponds to the temperature induced strain by making use of a transducer. And the shift in Bragg wavelength due to strain is given as

$$\Delta\lambda_B = \lambda_B(1 - p_e)\varepsilon \tag{2}$$

2.2. Temperature transducer

The temperature transducer converts the temperature information into mechanical force (displacement) by means of differential linear thermal expansion coefficients of two different ceramics. It can be assumed that α_1 and α_2 are linear thermal expansion coefficients of two ceramics, respectively. Whenever the transducer is subjected to the temperature by inserting it into a heat chamber/furnace the relative displacement between the two ceramic rods is given as [18]

$$\Delta L_d = L_{eff}(\alpha_1 - \alpha_2)\Delta T \tag{3}$$

where L_{eff} is the effective length of transducing element.

3. DESIGN AND SIMULATION

3.1. Design of sensor Probe

Fig. 1 shows the schematic of FBG temperature sensor probe, configured by pasting an FBG between two rigid supports which are maintaining a distance of temperature dependent. A ceramic rod made of Silicon Carbide with thermal expansion coefficients ~4 x10^{-6} /^{o}C and a ceramic Alumina rod with thermal expansion coefficients ~7 x10^{-6} /^{o}C are inserted into an Alumina sheath of thermal expansion coefficients ~7 x10^{-6} /^{o}C, respectively. The dimensions of the ceramic rods and sheath are taken as given in the Fig. 1. An FBG of resonance wavelength, 1553 nm is fixed between free end of the ceramic rod and open end of the sheath, with help of a ceramic adhesive. A metallic spring is used to update the axial strain on the FBG at any applied temperature. Here the arrangement of ceramic rods and spring acts as a transducer that converts temperature information into displacement information. Since the Silicon Carbide is having less linear thermal expansion coefficient rather than Alumina, the relative displacement of the free end of bimetallic strip with respect to open end of the sheath enables the FBG to be strained.

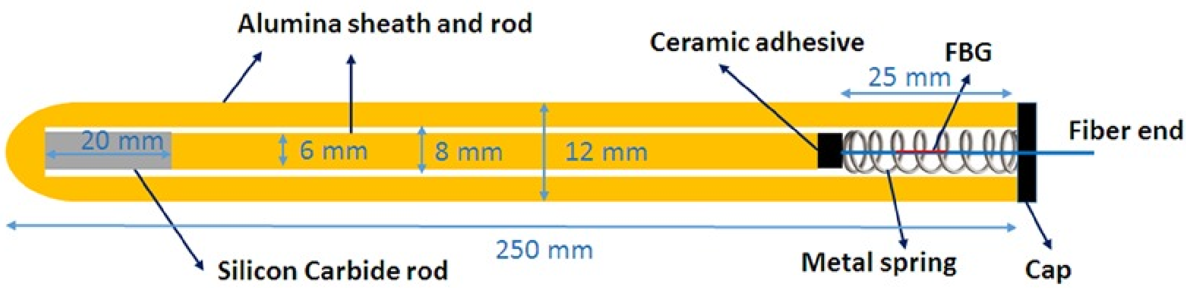

Figure 1. Schematic of sensor probe

3.2. Design of sensor system

Fig. 2 shows the schematic of experimental setup. A broad band light source (BBS) illuminates the FBG. The reflected peak power from FBG is directed to an optical spectrum analyzer (OSA). When the sensor probe is subjected to temperature by inserting it into a tubular furnace of the range 20-1500 ºC the shift in Bragg wavelength of FBG due to this temperature induced axial strain will be measured by using OSA.

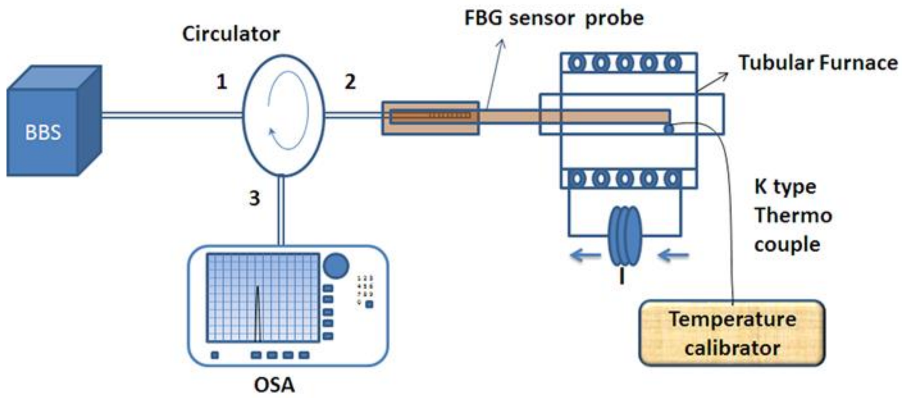

Figure 2. Schematic of experimental setup

3.3. Simulation

The sensor probe is configured by gluing an FBG of fiber length, 25 mm with the transducer as explained above, and the fiber end is connected to the measurement unit through an optical fiber patch cord with FC/PC connector. Subject to the temperature, the transducing element results in axial strain on the FBG, which can be given as

$$\varepsilon = \frac{\Delta L}{L} = \frac{-\Delta L_d}{L} = \frac{L_{eff}\,(\alpha_2 - \alpha_1)\Delta T}{L} \tag{4}$$

From Eq. 2 & Eq. 4

$$\Delta\lambda_B = \lambda_B(1 - p_e)\left[\frac{L_{eff}\,(\alpha_2 - \alpha_1)\Delta T}{L}\right] \tag{5}$$

where L is length of the fiber glued on transducer. The Eq. 5 is simulated using a MATLAB software, with parameters L= 25 mm, L_{eff}=20 mm, λ_B=1553 nm, P_e= 0.22, α_1 =~4 x10^{-6} /ºC, and α_2 =~7 x10^{-6} /ºC.

4. RESULTS AND DISCUSSION

Due to less thermal expansion coefficient of Silicon Carbide over Alumina, the temperature (heat) expands Alumina sheath comparatively more than Silicon Carbide rod, which results in axial strain on FBG. At the maximum applied temperature of 1500 ºC the relative displacement of free end of alumina rod is 89 µm. The maximum strain applied on the FBG of fiber length 25 mm is 3560×10^{-6}. From Fig. 3 it can be seen that the maximum shift in Bragg wavelength (at 1500ºC) is 4.31 nm and the temperature sensitivity of the sensor probe is 2.9 pm/ºC.

Since the strain limit of the fiber (a typical Germanosilicate fiber) is about 5000×10^{-6}, the FBG can be safe with the range of temperature, 20-1500 ºC. It is evident from the simulation results that the proposed sensor can be adapted for high temperature measurement up to 1500 ºC. The experimental work is under progress.

5. CONCLUSION

An FBG based high-temperature sensor system has been designed and simulated. The results revealed that the sensor can be adapted for high temperatures measurement, up to 1500 ºC. The important aspects that are involved in this design are; i) design of a rigid sensor probe using a standard FBG for enhanced temperature range and ii) making a short length of probe active to the temperature whereas the other portion remains inactive, which stabilize the sensor response by making it independent of length of the probe subjected to the temperature.

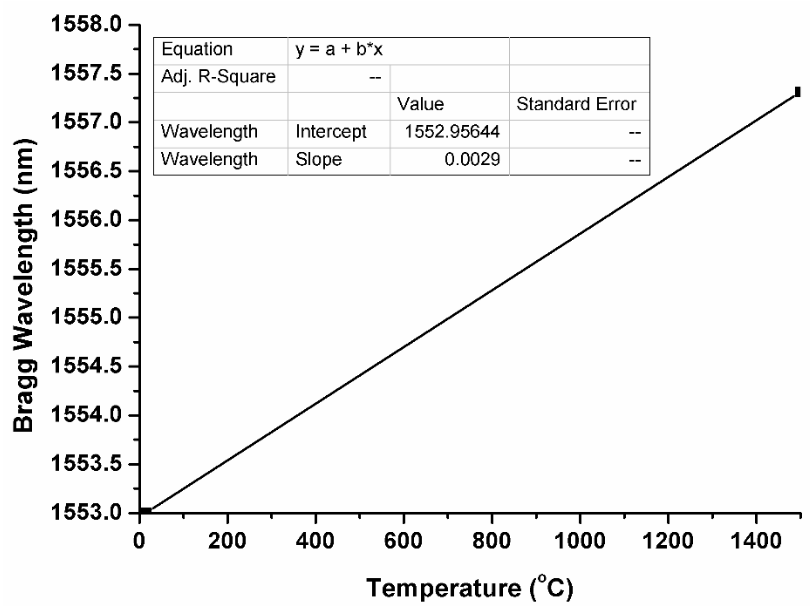

Figure 3. Bragg wavelength versus temperature by simulation

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