FBG-based Novel Sensor for High-temperature Measurement and Its Low-cost Interrogation

M. Venkata Reddy*, K. Srimannarayana, R.L.N. Sai Prasad, T. V. Apparao, P. Vengal Rao
Department of Physics, National Institute of Technology, Warangal-506004, India

ABSTRACT

A novel sensor for high-temperature measurement using Fiber Bragg grating (FBG) along with its low-cost interrogation system has been designed and tested. 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 materials, stainless steel and mild steel. The shift in Bragg wavelength of FBG due to this temperature induced strain is measured by using optical spectrum analyser (OSA). Further the bulk and expensive OSA is replaced by a low cost interrogation system that employed an LPG, a photodiode, a transimpedance amplifier, and a digital multimeter. The LPG converts wavelength information of FBG into its equivalent intensity modulated signal which is captured by a simple photodiode and then converted into voltage signal using the transimpedance amplifier. The designed sensor measures the temperature from 20°C to 1000°C with a resolution of 2°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].

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 [4]. 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 [5,6]. 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 [4,7]. However, femtosecond infrared (Fs-IR) laser induced Type-II gratings and regenerated gratings have been proved to withstand higher-temperature [8,9], but are limited by short term stability at high temperature [7,10-12]. So, there is a necessity to develop an alternative technique which enables high-temperature measurement using FBG sensors [13]. Besides, the wavelength encoded information from FBG can be captured only by using an optical spectrum analyser (OSA) which significantly increases the size and cost of the system and is limited by low scanning speed [14,15]. Hence, for successful utilization of the technology in engineering applications there is necessity to develop a compact and low cost interrogation system along with an FBG-based high temperature sensor.

In this article we describe a novel design of an FBG-based sensor and its low cost interrogation scheme enable to measure the temperatures of up to 1000 °C.

*vrmamidi@nitw.ac.in; Phone: +91-870-2462592; Fax: +91-870-2459547; www.nitw.ac.in

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2. WORKING PRINCIPLE

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]

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

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 metallic strips. It can be assumed that α_1 and α_2 are linear thermal expansion coefficients of two metallic strips, respectively. Whenever the transducer is subjected to the temperature by inserting it into a heat chamber/furnace the relative displacement between the two metallic strips is given as

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

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

2.3. Wavelength interrogation

Long period grating (LPG) having spectral loss at selected wavelength can be used as a linear response edge filter, that converts wavelength shifts into intensity modulations. The reflected peak power of FBG gets modulated according to the LPG transmitted power at corresponding wavelengths. This intensity modulated signal can be detected by a simple photodiode (PD) with accompanied electronic circuitry [17].

3. EXPERIMENTAL DETAILS

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 bimetallic strip of stainless steel and mild steel having linear thermal expansion co-efficients 17 x10^{-6} /ºC and 12 x10^{-6} /ºC, respectively (24 cm + 6 cm) is joined inside a rectangular metallic frame made of SS. Since the difference in thermal expansion coefficients of stainless steel and mild steel is ~5 x10^{-6} /ºC, the free end of bimetallic strip get shifted 300 µm away from the rectangular frame at the maximum applied temperature of 1000 ºC. A fiber of length of 10 cm containes an FBG of resonance wavelength at 1552.98 nm is glued between free end of the bimetallic strip and outer frame. The designed sensor probe is connected to the measurement unit through an optical fiber patch card with FC/PC connector.

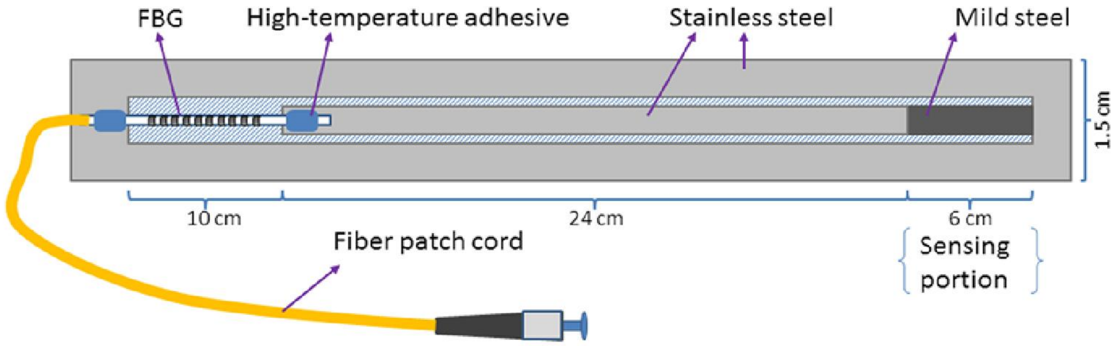

Figure 1. Schematic of sensor probe

3.2. Sensor working

Fig. 2 shows the schematic of experimental setup. A broad band light source (BBS) is used to illuminate the FBG. The reflected peak power from FBG is directed to OSA using a 3-port circulator. And temperature is applied to the sensor head by inserting its fixed end of bimetallic strip into a tubular furnace of the range 20-1000 ºC. When the temperature is increased, the bimetallic strip along with its metallic frame tends to be expanded. Here the arrangement of bimetallic strip acts as a transducer that converts temperature information into displacement information. Since the mild steel is having less linear thermal expansion coefficient rather than stainless steel, the relative displacement of the free end of bimetallic strip with respect to outer frame enables the FBG to be strained. Then the shift in Bragg wavelength of FBG due to this temperature induced axial strain is measured by using OSA.

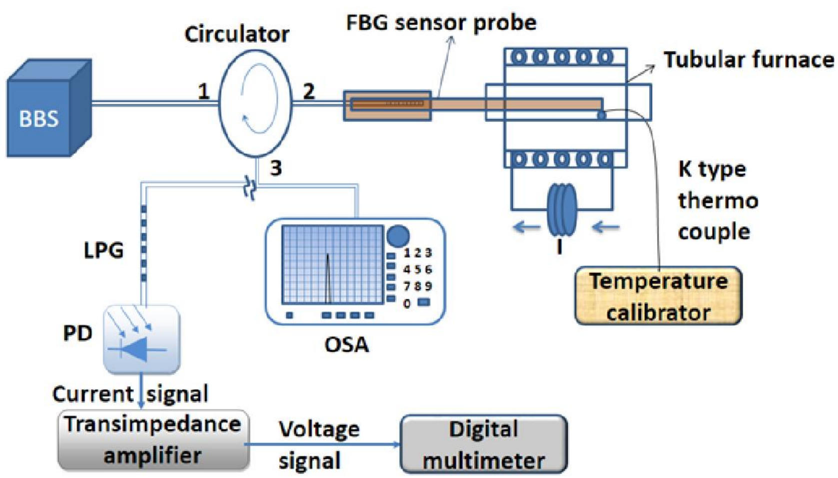

Figure 2. Schematic of experimental setup.

3.3. Interrogation Scheme

Further the bulk and expensive OSA is replaced by a low cost interrogation system that employed an LPG, a photodiode, a transimpedance amplifier, and a digital multimeter. The LPG converts wavelength information from FBG into its equivalent intensity modulated signal which can be captured by a simple PD and then converted into voltage signal by making use of a transimpedance amplifier. This temperature related voltage output is measured using a digital multimeter. Fig. 3. Shows photograph of the experimental setup.

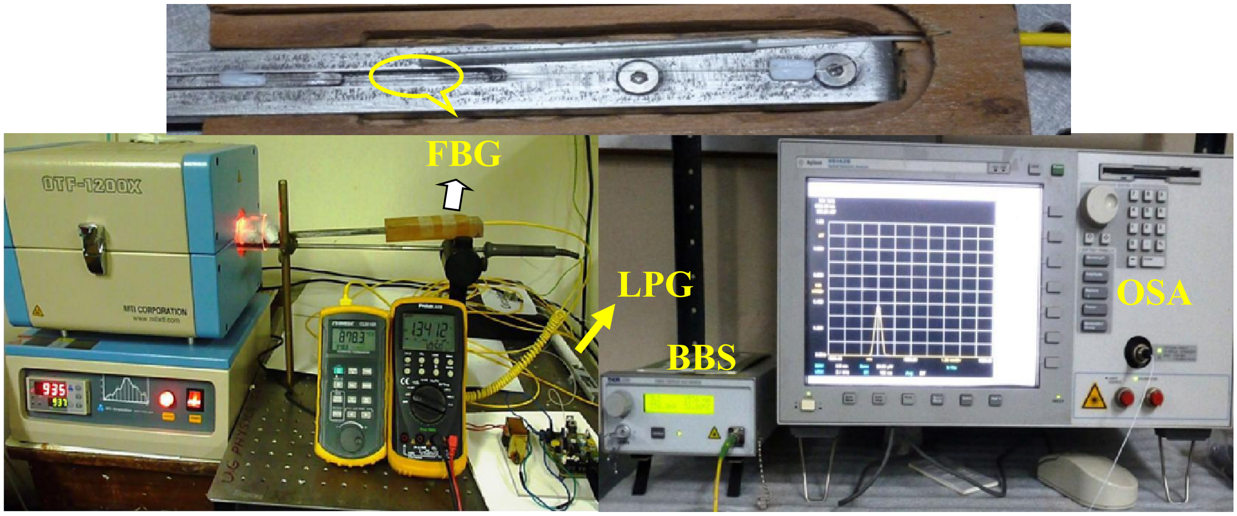

Figure 3. Photographs of experimental setup

4. RESULTS AND DISCUSSION

Fig. 4 shows the temperature response of the sensor in terms of Bragg wavelength as well as voltage. It can be observed from the plot that as temperature increased up to 1000 ^{o}C the Bragg wavelength got red-shifted. Since the experiment is carried out in laboratory conditions (air conditioning room), the temperature surrounding to the FBG is maintained constant (20 ^{o}C). The only impact on FBG that is responsible for the shift in Bragg wavelength is the temperature induced strain. Hence there is no issues/limitations in using FBG for high temperature measurement. It is observed from experimental results that the shift in Bragg wavelength is having an exponential correlation with the applied temperature due to the thermal expansion coefficient of SS which is exponentially correlated with temperature. As the sensor system employed a transducer based on differential thermal expansion of SS frame and steel strip, only a selected length of the sensor probe is acted as sensing portion, shown in Fig. 1. So the shift in Bragg wavelength at 1000 ^{o}C is found to be 3.6 nm.

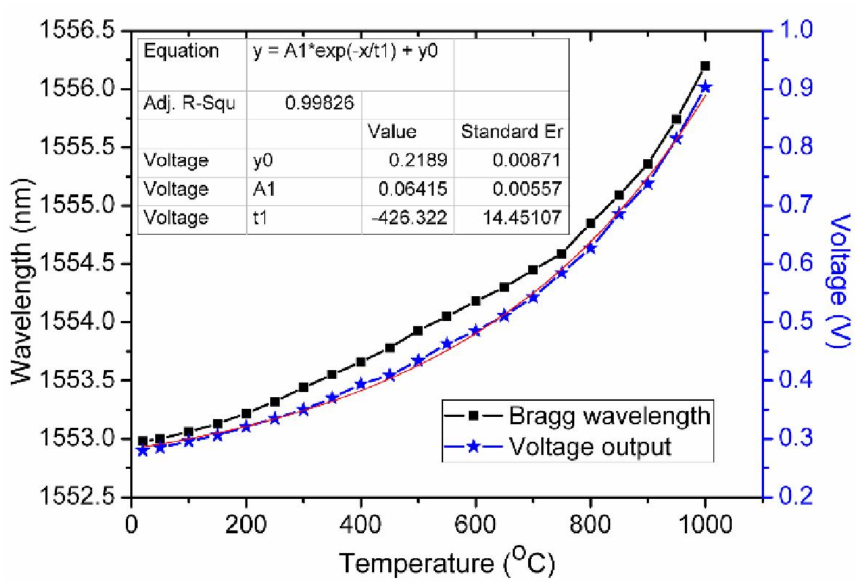

Figure 4. Temperature response of FBG sensor in term of Bragg wavelength and voltage.

After low cost interrogation of wavelength information the sensor output is extracted into voltage signal, shown in Fig. 4. The sensitivity and resolution of the sensor at room temperature are found 16 mV/ºC and 2 ºC, respectively, and both of them are found to be increased as moving toward high-temperature. Fig. 5 shows the calibration of the sensor, and the relation between sensor output and temperature to be displayed.

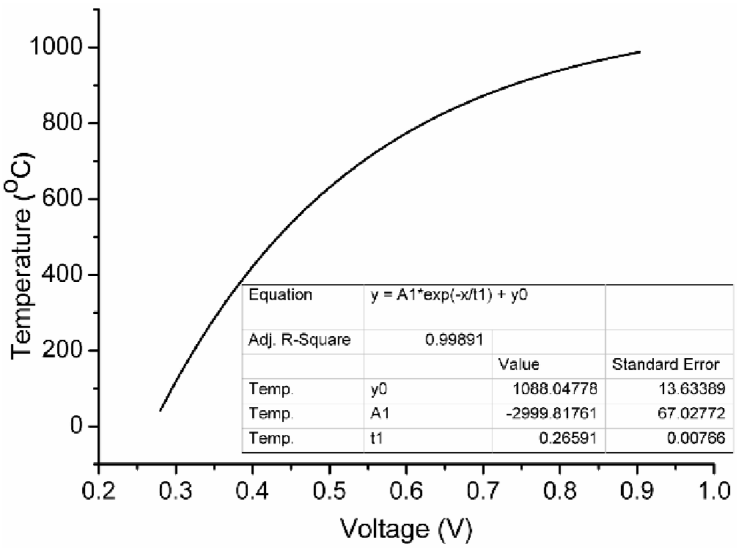

Figure 5. Sensor calibration.

5. CONCLUSION

An FBG based high-temperature sensor system has been designed, developed, and tested. The test results revealed that the sensor is able to measures the temperature from 20 ºC to 1000 ºC with 2 ºC resolution. The important aspects that are involved in this design are; i) design of a rigid sensor probe using FBG for enhanced temperature range, 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, and iii) making the measurement system cost effective by replacing the OSA with a low cost interrogation system.

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