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A novel fiber Bragg grating high-temperature sensor ☆

Yage Zhan[a,*], Shaolin Xue[a], Qinyu Yang[a], Shiqing Xiang[b], Hong He[b], Rude Zhu[b]

[a]Department of Applied Physics, College of Science, Donghua University, Shanghai 201620, China
[b]Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

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Abstract

A novel fiber Bragg grating (FBG) sensor for the measurement of high temperature is proposed and experimentally demonstrated. The interrogation system of the sensor system is simple, low cost but effective. The sensor head is comprised of one FBG and two metal rods. The lengths of the rods are different from each other. The coefficients of thermal expansion of the rods are also different from each other. The FBG will be strained by the sensor head when the temperature to be measured changes. The temperature is measured basis of the wavelength shifts of the FBG induced by strain. A dynamic range of 0–800 °C and a resolution of 1 °C have been obtained by the sensor system. The experiment results agree with theoretical analyses.

Keywords: Sensor; Fiber Bragg grating; High temperature

1. Introduction

Reliable high-temperature sensors are important and indispensable in some fields, such as in some structure health monitoring and material processing, electrical transformer, petroleum pipeline and so on [1,2]. Traditional electrical high-temperature sensors have some disadvantages, including low reliability, large temperature fluctuation and latent danger of fire accident. Optical fiber Bragg grating (FBG) sensors have numerous advantages over traditional electrical sensors, such as immunity to electromagnetic interference, higher stability and sensitivity, more easiness of multiplex, being competent for application in harsh environments, "smart structures" and on-site measurements [3,4]. FBG sensors are the most appropriate sensors for monitoring applications in the fields mentioned above. But common FBG sensors cannot used directly as high-temperatures sensor because they will be decayed when its temperature higher than 200 °C and will be destroyed when its temperature higher than 350 °C [5,6]. Until now, only a very few kind of technologies on FBG high-temperature measurement have been researched [7,8]. Brambilla et al. have researched the high-temperature measurement characteristics of FBGs that with special dopants (such as Sn and/or Na_2O). They discovered that these FBGs exhibit unusual oscillations in reflectivity [9]. These methods are not suited for high-temperature measurement.

This paper proposes a novel kind of FBG high-temperature sensor. The novel sensor is very suited for high-temperature object, especially for high-temperature object in usual temperature atmosphere. The experimental results and the characteristic of the sensor system are also described. The sensor is based on a novel FBG

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*Corresponding author.
E-mail address: ygzhan@yahoo.com.cn (Y. Zhan).

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sensor head and a fiber long period grating (LPG) as a linear edge filter for interrogation. The novel sensor head has been designed, prepared and used in high-temperature measurement experiments successfully. A dynamic range of 0–800 °C and a resolution of 1 °C have been experimentally achieved. Experimental results agree with theoretical analyses.

2. Theoretical analyses

2.1. Principle of sensor head

Sensor head is very crucial in sensor system. But common FBG cannot be used as high-temperature sensor head directly. We have designed a novel high-temperature FBG sensor head. The sensor head is mainly comprised of a FBG and two metal rods, as shown in Fig. 1. The two metal rods have different length and different coefficient of thermal-expansion (CTE). The lengths of the two metal rods are L_1 and L_2, respectively. The CTEs of the two metal rods are α_1 and α_2, respectively. The rods are fixed into one adiabatic plate. In order that there is not transverse thermal radiation, the two metal rods have been protected by adiabatic cylinder1 and adiabatic cylinder2, respectively. The left ends of the two metal rods connect two adiabatic rods, respectively. The FBG is pre-strained and glued to the end surface of the adiabatic rods on points A and B. The FBG is protected by the adiabatic cylinder3 in order that the FBG is not be modulated by the environmental temperature and the thermal radiation of the adiabatic plate.

The sensing ends (see also in Fig. 1) touch the object whose temperature to be measured. When temperature to be measured is changed, the two metal rods will have different elongation, which will make L change (the distance between the two adiabatic rods) and the FBG be strained. The temperature is measured basis of wavelength shifts of the FBG.

The adiabatic cylinders are effective. The transverse thermal radiation of the metal rods is negligible. When the rods are in heat balance, the temperature of each metal rod reduces linearly from whose sensing end

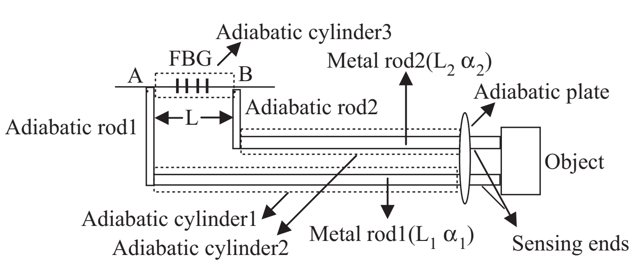

Fig. 1. Schematic diagram of sensor head structure.

to the other end. For briefness, the length change of L is given by

$$\Delta L_1 = \sum_{j=1}^{n} l_{1j}\Delta T_{1j}\alpha_{1j}(j = 1, 2, \ldots, n), \tag{1}$$

$$\Delta L_2 = \sum_{j=1}^{n} l_{2j}\Delta T_{2j}\alpha_{2j}(j = 1, 2, \ldots, n), \tag{2}$$

$$\Delta L = \Delta L_1 - \Delta L_2, \tag{3}$$

where ΔL_1 and ΔL_2 are the elongations of the two metal rods, respectively. ΔL is the length change of L, namely the elongation of FBG section of fiber. l_{ij}, ΔT_{ij} and α_{ij} $(i = 1,\ 2)$ are the length, average temperature and average CTE of the jth subsection of the metal rod. The corresponding wavelength shift $\Delta\lambda_B$ of the FBG is expressed by [3,10]

$$\Delta\lambda_B = \lambda_B(1 - p_e)\ \ \varepsilon = \lambda_B(1 - p_e)\frac{\Delta L}{L} = \lambda_B(1 - p_e)\frac{\Delta L_1 - \Delta L_2}{L}, \tag{4}$$

where $p_e = -(1/\varepsilon)(\Delta n_{eff}/n_{eff}) = (n_{eff}^2/2)[p_{12} - v(p_{11} + p_{12})]$ is the effective photo-elastic coefficient of the glass fiber with Possion ratio v. P_{11} and P_{12} are the photo-elastic coefficients of fiber. n_{eff} is the effective refractive index of the guide mode in the fiber. For a typical fused silica fiber, $p_e = 0.22$.

The two metal rods of the sensor head are made from an H62 brass rod and a 45# carbon steel rod, respectively. The CTEs of the two metal rods are α_1 and α_2, respectively. α_1 and α_2 have been measured and determined numerically by

$$\alpha_1 = \left(15.78250 + 0.02796 \times T - 2.4085 \times 10^{-5} \times T^2\right) \times 10^{-6},$$
$$\alpha_2 = \left(10.99550 + 0.00994 \times T - 5.5421 \times 10^{-5} \times T^2\right) \times 10^{-6}. \tag{5}$$

In the same temperature range, α_1 is larger than α_2. The lengths of the two rods are L_1 and L_2, respectively. The curve of the wavelength change of the FBG have been theoretically simulated with suppositions of both $L_1 = 20$ cm, $L_2 = 18$ cm and $L_1 = 18$ cm, $L_2 = 20$ cm in the range of 0–500 °C. The simulation results are shown in Fig. 2. Similarly, the simulation results in the range of and 0–1000 °C are shown in Fig. 3.

If $L_1 = 20$ cm and $L_2 = 18$ cm, the peak wavelength of the FBG shifts almost linearly with temperature in the range of 0–800 °C. When the temperature ascends from 0 to 800 °C, it shifts 6.80 nm. Generally, 6.8 nm wavelength shift will not induce the FBG worse or broken.

The sensitivity of the sensor system is enhanced when the metal rod with larger CTE is longer than the metal rod with smaller CTE, which can be confirmed by that