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Fiber grating sensors for high-temperature measurement

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Abstract

Two fiber grating sensors for high-temperature measurements are proposed and experimentally demonstrated. The interrogation technologies of the sensor systems are all simple, low cost but effective. In the first sensor system, the sensor head is comprised of one fiber Bragg grating (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 based on the wavelength-shifts of the FBG induced by the strain. In the second sensor system, a long-period fiber grating (LPG) is used as the high-temperature sensor head. The LPG is very-high-temperature stable CO_2-laser-induced grating and has a linear function of wavelength–temperature in the range of 0–800 °C. A dynamic range of 0–800 °C and a resolution of 1 °C have been obtained by either the first or the second sensor system. The experimental results agree with theoretical analyses.

Keywords: Optical fiber sensor; Fiber Bragg grating; Long-period fiber grating; High temperature

1. Introduction

In some fields, such as tunnel monitoring, material processing, mine monitoring, structure health monitoring and oil well monitoring, reliable high-temperature sensors are necessary and important [1,2]. Traditional electrical high-temperature sensors have some disadvantages, including large temperature fluctuation, latent danger of fire accident and low reliability. Optical fiber grating sensors have numerous advantages over traditional electrical sensors, such as higher stability and sensitivity, immunity to electromagnetic interference, being competent for application in harsh environments, "smart structures" and on-site measurements [3,4]. So, fiber grating sensors are the most appropriate sensors for applications in the fields mentioned above.

Fiber Bragg grating (FBG) and fiber long-period grating (LPG) are usually used as temperature sensor heads. But neither the common FBG nor the common LPG can be used directly as high-temperature sensor heads, because they will be decayed when the temperature is higher than 200 °C and will be destroyed when the temperature is higher than 350 °C [5,6]. So, until now, only a very few kinds of technologies on FBG or LPG high-temperature measurement have been researched [7,8]. Brambilla et al. [9] have researched the high-temperature measurement characteristics of FBGs with special dopants (such as Sn and/or Na_2O). They discovered that these FBGs exhibited unusual oscillations of reflectivity [9]. These methods are not suited for high-temperature measurements.

This paper proposes two fiber grating high-temperature sensors, based on a FBG with a novel designed structure as the sensor head and a special high-temperature stable LPG as the sensor head, respectively. The experimental results and the characteristics of the sensor systems are also discussed. The two high-temperature sensor heads have been designed, prepared and used in experiments successfully. A dynamic range of 0–800 °C and a resolution of 1 °C have been experimentally achieved by either the first or the second sensor system. Experimental results agree with the theoretical analyses.

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2. Theoretical analyses

2.1. Principle of the first high-temperature sensor head

Common FBG can't be used as a high-temperature sensor head directly, so a novel high-temperature FBG sensor head has been designed. The sensor head is mainly comprised of a FBG (FBG_1) and two metal rods, as shown in Fig. 1. The two metal rods have different lengths and different coefficients 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. Adiabatic cylinders 1 and 2 are used to protect the two metal rods, in order that there is no transverse thermal radiation. The left ends of the two metal rods connect the two adiabatic rods. FBG_1 is pre-strained and glued to the end surface of the adiabatic rods on point A and point B. FBG_1 is protected by adiabatic cylinder 3 in order that FBG_1 is not modulated by the environment temperature and the thermal radiation of the adiabatic plate.

The sensing ends (see Fig. 1) touch the object whose temperature is to be measured. When the temperature to be measured changes, the two metal rods will have different elongations, which will make L change (the distance between the two adiabatic rods) and FBG_1 be strained. The temperature is measured on the basis of wavelength shifts of FBG_1.

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 one sensing end to the other end. Briefly, the length change of L is given by

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

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

where ΔL_1 and ΔL_2 are the elongations of the two metal rods, respectively. $\Delta L = \Delta L_1 - \Delta L_2$ and ΔL is the length change of L, namely the elongation of FBG_1 section of the 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 of FBG_1 ($\Delta\lambda_{B1}$) is expressed by [3,10]

$$\Delta\lambda_{B1} = \lambda_{B1}(1 - p_e)\varepsilon = \lambda_{B1}(1 - p_e)\frac{\Delta L}{L} = \lambda_{B1}(1 - p_e)\frac{\Delta L_1 - \Delta L_2}{L}, \tag{3}$$

where

$$p_e = -\frac{1}{\varepsilon} = \frac{n_{eff}^2}{2}[p_{12} - v(p_{11} + p_{12})]$$

is the effective photo-elastic coefficient of the glass fiber with the Poisson 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 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

$$\alpha_1 = (15.78250 + 0.02796 \times T - 2.4085 \times 10^{-5} \times T^2) \times 10^{-6},$$
$$\alpha_2 = (10.99550 + 0.00994 \times T - 5.5421 \times 10^{-5} \times T^2) \times 10^{-6}. \tag{4}$$

In the same temperature range, α_1 is larger than α_2. The curve of the wavelength of FBG_1 has 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 0–1000 °C as shown in Fig. 2.

If $L_1 = 20$ cm and $L_2 = 18$ cm, the Bragg wavelength of FBG_1 shifts almost linearly with temperature in the range of 0–800 °C. When the temperature ascends from 0 to 800 °C, it shifts 6.89 nm. The sensitivity of the sensor is enhanced when the metal rod with a larger CTE is longer than the metal rod with a smaller CTE, which can be confirmed by that the slope of the curve (a) is larger than the slope of the curve (b) in Fig. 2. So the experiments are

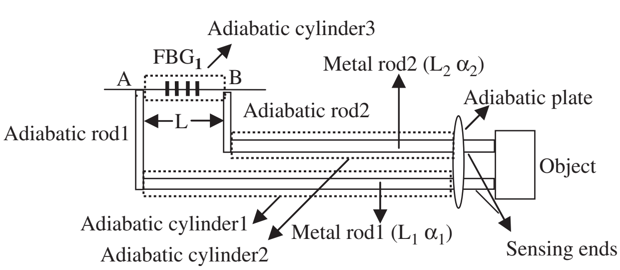

Fig. 1. Schematic diagram of the first sensor head.

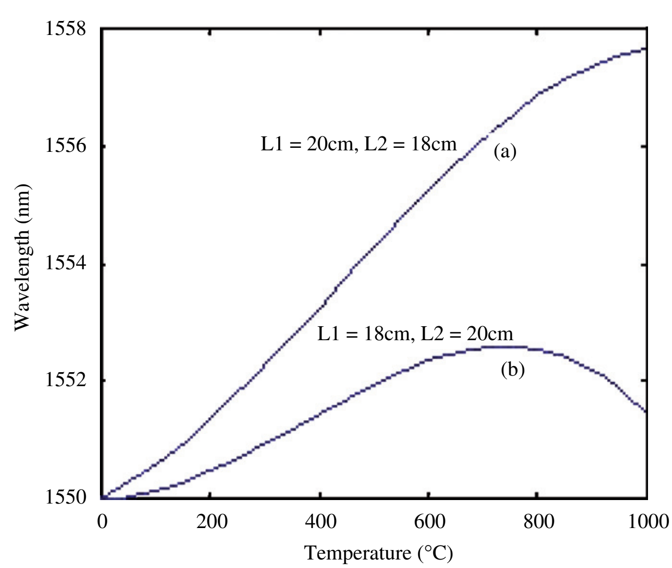

Fig. 2. Temperature–wavelength response of FBG_1 in the range of 0–1000 °C.