Optica Applicata, Vol. XL, No. 3, 2010

A novel method for high temperature measurements using fiber Bragg grating sensor

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This paper reports the simulation, design and experimental analysis of a fiber Bragg grating (FBG) temperature sensor, making use of chemical composition grating (CCG), which ranges from room temperature to over 900 °C. The interrogation system of the sensor proposed is simple, effective and of low cost. The sensor head comprises FBG attached to a metal plate that will be strained due to change in the length of the plate with increase in temperature. The temperature is measured on the basis of the reflected Bragg wavelength shifts from the FBG. The dynamic range of the sensor is about 30 °C to 900 °C. The proposed sensor can be employed for monitoring the health of structural members at elevated temperatures. The dynamic range of the sensor can be increased to beyond 1500 °C by making use of FBG made up of sapphire instead of silicon fiber.

Keywords: fiber Bragg grating, chemical composition grating, long period grating, broadband source, 3 dB coupler, optical spectrum analyzer.

1. Introduction

Harsh environments involving extreme physical conditions, *e.g.*, high temperature, high pressure, chemical aggressive media, strong electromagnetic interface (EMI), and high-energy radiation exposure are often unavoidable in many industrial applications, such as power generation and distribution systems, metal and glass manufacturing industries, and nuclear power industries, *etc*. Accurate and reliable measurement of temperature is essential for safe and efficient operation and control of these industrial processes. Under these severe environmental conditions, it is very difficult to apply conventional sensors and measuring devices such as high-temperature thermocouples, resistance temperature devices, and acoustic pyrometers, *etc*.

Optical temperature sensors possess some unique advantages over conventional electrical and acoustic temperature sensors, *e.g.*, high sensitivity, compact size, immunity to EMI and harsh corrosive environment, and reliable measurements can be made at elevated temperatures [1]. FBG sensors are presently replacing many of the conventional sensors for such high temperature measurements. This paper proposes a high sensitive optical temperature measurement technique, based on FBG, for real--time measurement of temperature in harsh environments.

2. Principle of FBG sensor

Fiber gratings are broadly classified into two categories: fiber Bragg grating and long period grating (LPG). The FBG typically has period less than micrometer. It couples light from the forward guided mode to the backward guided mode and cladding mode and thus, produces Bragg reflections and many small dips in transmission at shorter wavelength side of the Bragg wavelength. The LPG, which has period of hundreds of micrometers, couples light from the guided mode to the forward cladding mode resulting in attenuation bands in the transmission spectrum [2].

Theoretically, the normalized reflection produced by a FBG is given by [3]

$$R = \frac{\sinh^2\left[kL\sqrt{1-(\delta/k)^2}\right]}{\cosh^2\left[kL\sqrt{1-(\delta/k)^2} - (\delta/k)^2\right]} \tag{1}$$

where δ/k is the detuning ratio, the detuning parameter for Bragg grating of period Λ is $\delta = \Omega - (\pi/\Lambda)$, $\Omega = 2\pi n_{\mathrm{eff}}/\lambda$, $k = \pi\eta/\lambda_B$ is coupling coefficient and η is calculated over the fiber core of Bragg grating. In this case $\eta = \Delta n F$, where $F = 1 - (1/v^2)$.

The normalized power transmitted by the fundamental guided mode through the LPG is given by

$$T = \frac{\cos^2\left[k^{(m)}L\sqrt{1+\delta^{(m)}/k^{(m)}}\right] + \left(\delta^{(m)}/k^{(m)}\right)^2}{1+\delta^{(m)}/k^{(m)}} \tag{2}$$

and all specified parameters in the above case now depend on the mode number m.

FBG is composed of periodic changes of the refractive index that is formed from exposure to an intense UV interference pattern in the core of an optical fiber [4]. This grating structure results in the reflection of light at a specific narrowband wavelength, called the Bragg wavelength. The Bragg condition is expressed as $\lambda_B = 2n_{\mathrm{eff}}\Lambda$, where λ_B is the Bragg wavelength of FBG, n_{eff} is the effective index of the fiber core, and Λ is the grating period. The wavelength, which is determined by the Bragg condition, gets reflected at the Bragg grating part and the other wavelengths pass through it. Figure 1 shows this process.

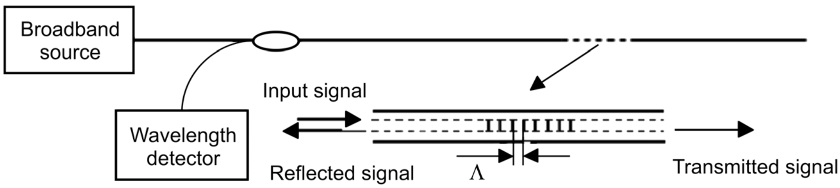

Fig. 1. Schematic diagram of fiber Bragg grating sensor wavelength-encoding operation.

The Bragg wavelength is a function of the refractive index of the fiber core and the grating period. If the grating is exposed to external environmental conditions, such as strain and temperature, the Bragg wavelength shifts. By measuring the wavelength shifts accurately, we can measure material properties like strain and temperature. This is the fundamental principle that allows fiber Bragg grating to be used as a sensor. The shift of a Bragg wavelength due to strain and temperature can be expressed as

$$\Delta\lambda_B = \lambda_B\left[(\alpha_f + \xi_f)\Delta T + (1 - p_e)\varepsilon\right] \tag{3}$$

where α_f is the coefficient of thermal expansion, ξ_f is the thermo-optic coefficient and p_e is the strain-optic coefficient of the optical fiber. Here, total wavelength shift ($\Delta\lambda_B$) is due to the combination of strain and temperature effects.

2.1. Chemical composition of FBG sensor

The development of FBGs that are suitable for high-temperature applications is becoming increasingly important in sensing and high-power laser applications. Previous studies have already established that operable temperatures of FBGs can be increased by several means, including tailoring the glass composition, preprocessing with seed irradiation and the formation of type-IIA and type-II gratings using femtosecond IR lasers. Another method with superior high temperature stability is to make use of chemical composition grating (CCG) [5] in which a periodic index modulation can be regenerated after exposure to the UV-induced type-I grating written in hydrogen loaded germanosilicate fiber that happens to contain fluorine, when annealed at 1000 °C. The prediction for this index modulation happens to be a local reduction of fluorine in the UV-exposed zones at that high temperature through diffusion of hydrogen fluoride [6]. A subsequent study on annealing of type-I gratings at high temperatures, however, has shown that the presence of fluorine is not necessary for this regeneration of index modulation. CCGs can also be formed in Er-doped fiber with dopants such as Ge, Al and Sn. Very recently the phenomenon of regeneration has also been found in simple hydrogen loaded germanosilicate fiber.

Grating (L = 5 mm) has been inscribed using an ArF exciplex laser (193 nm, T_w = 15 ns, f_{pulse} = 40–70 mJ/cm^2, repetition rate = 10 Hz, $f_{\text{cumulative}}$ = 360 J/cm^2) in

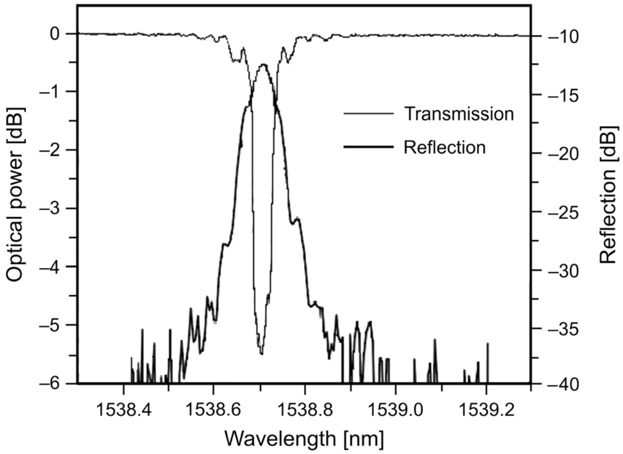

Fig. 2. Measured transmission and reflection spectrum of chemical composition grating.

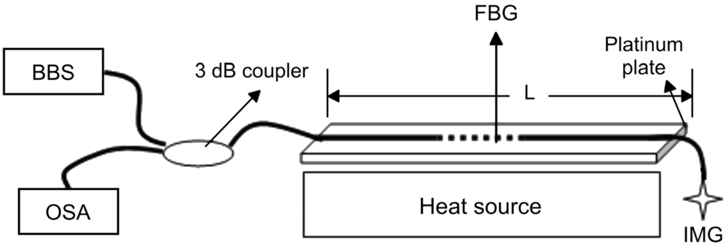

Fig. 3. Schematic diagram of proposed sensor head.

B/Ge-doped silica fiber (core: 20 mol% B, 33 mol% GeO_2; inner cladding: 11 mol% P, < 4 mol% F). It was loaded with hydrogen (180 atm, 24 hrs) while the fiber is placed under tension with a standard load ~100 g. The transmission and reflection spectra of the CCG [7] used in the present work are given in Fig. 2.

3. Theoretical analysis of proposed sensor head

The sensor head is very crucial in any sensing system. The proposed sensor head mainly comprises a FBG firmly glued onto the surface of a platinum metal plate having length L with coefficient of thermal expansion α. The schematic experimental set-up depicting the sensor head is as shown in Fig. 3.

The temperature is measured on the basis of the shift in wavelength of the FBG reflection peak. When the plate and FBG are in heat balance, due to the change in temperature difference, the change in the length of the plate can be expressed as

$$\Delta L = \sum_{j=1}^{n} L_j \Delta T_j \alpha_j, \quad j = 1, 2, 3, ..., n \tag{4}$$

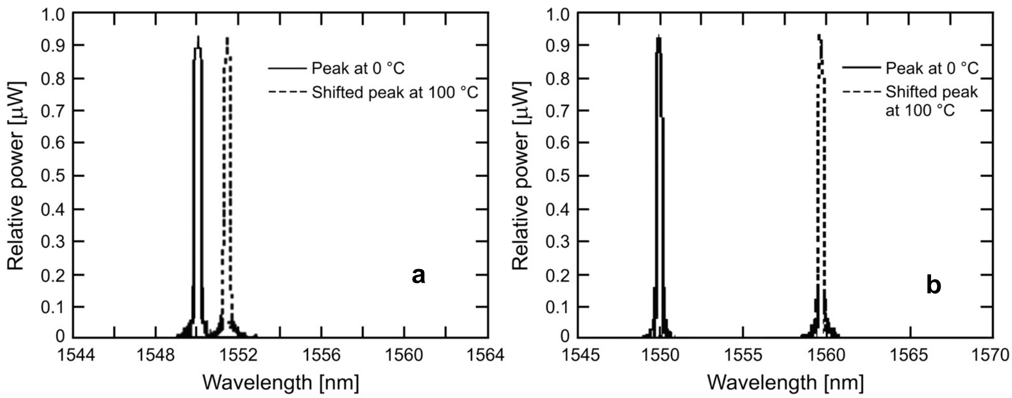

Fig. 4. Reflected peak shifts at different temperatures: shift at 100 °C (**a**), shift at 900 °C (**b**).

where ΔL is the change in length of the plate, and it in turn elongates the FBG section of the fiber.

The corresponding wavelength shift $\Delta\lambda_B$ of the FBG is expressed by

$$\begin{aligned} \Delta\lambda_B &= \lambda_B(1-p_e)\varepsilon \\ \Delta\lambda_B &= \lambda_B(1-p_e)\frac{\Delta L}{L} \end{aligned} \tag{5}$$

where $p_e = (n_{\rm eff}^2/2)[p_{12} - v(p_{11} + p_{12})]$ is the effective photo-elastic coefficient of the glass fiber with Poisson's ratio v, p_{11} and p_{12} are the photo-elastic coefficients of the fiber, $n_{\rm eff}$ is the effective refractive index of the guide mode in the fiber. The $n_{\rm eff}$ of the silica fiber and Poisson's ratio are taken as 1.482 and 0.16, respectively. The effective photo-elastic coefficient is taken as $p_e = 0.22$.

The plot of the wavelength change of the FBG have been theoretically simulated by taking the length of platinum metal plate [8] of 3.0 cm and the results are presented in Fig. 4. At 100 °C, 500 °C and 900 °C the wavelength shifts are found to be 1 nm, 5 nm and 9 nm, respectively.

3.1. Interrogation principle and the experimental set-up of the FBG sensor

Wavelength interrogation technology is very important for any FBG sensor system. In the present high temperature sensor system, an LPG is used as a linear response edge filter to convert wavelength into intensity encoded information for interrogation, by utilizing the linear portion of the LPG transmitted spectrum. The interrogation system and the experimental set-up are shown in Fig. 5. Light from the broadband source (BBS) gets modulated by the LPG and then illuminates the FBG in the sensor head via 2×2 coupler. After being LPG modulated, the transmitted light has a section of linear spectrum. The reflected peak power from FBG is thus modulated according to LPG transmitted linear portion of the spectrum [9]. The reflected peak power of

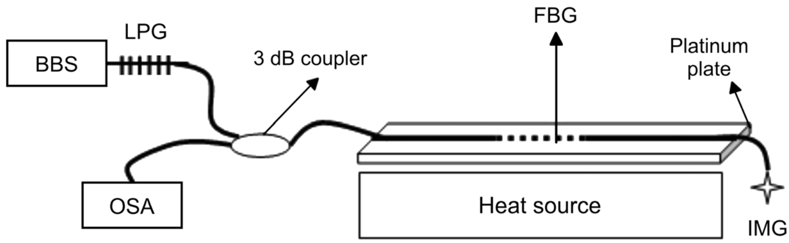

Fig. 5. Schematic diagram of the sensor system with LPG as interrogation element.

FBG is high at lower temperatures and as temperature increases, the reflected peak shifts to the negative slope of the LPG spectrum. Accordingly, the peak power of FBG reduces, as shown in Fig. 6. The reflected light from the FBG will be detected by OSA.

The filtering mechanism of the LPG [10] yields a linear relationship between the wavelength shift of FBG and the detected light intensity at different temperatures [11]. The Bragg wavelength of FBG is located at the intensity-descending side

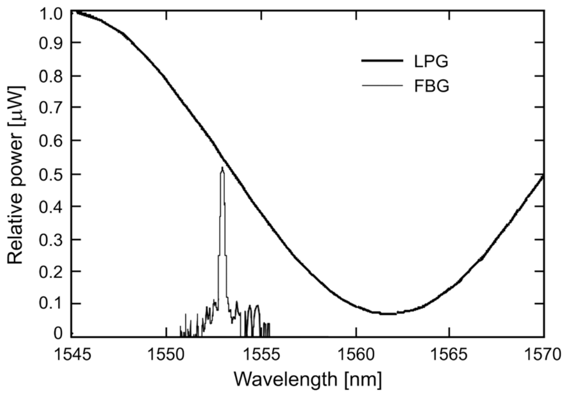

Fig. 6. Schematic spectra of FBG temperature sensor and LPG employed as edge filter.

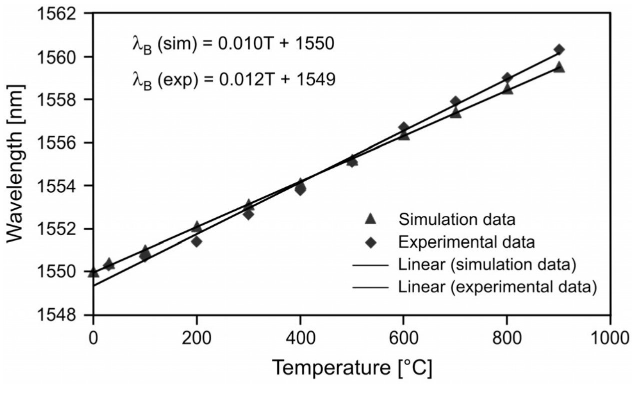

Fig. 7. Simulation and experimental results of high temperature FBG sensor.

of the transmitted band of LPG, *i.e.*, at the LPG curve with negative slope [12], thereby making the reflected FBG power decrease when λ_B shifts to the longer wavelength as shown in Fig. 6. By varying temperature from 30 °C to 900 °C, the Bragg wavelength shift is noted, and a graph is plotted between temperature and wavelength as shown in Fig. 7.

3.2. Results and discussion

The graphical data for simulated and experimental values have been fitted by polynomial functions: $\lambda_B(\mathrm{sim}) = 0.010T + 1550$, and $\lambda_B(\mathrm{exp}) = 0.012T + 1549$; where λ_B is the Bragg wavelength of FBG and T is the temperature to be measured. The simulated and experimental results are in very close agreement with each other.

The temperature sensitivity of the system with MATLAB simulation is found to be 11.11 pm/°C with a linearity of 99.9%, where it was found to yield a sensitivity of 11.44 pm/°C with a linearity of 99.7% experimentally. The grating was stable and continued to survive throughout the experiment up to 900 °C. These results indicate that it is possible to fabricate gratings with CCGs that perform reliably as ultra high temperature components and sensors in excess of 1000 °C.

4. Conclusions

A novel high temperature FBG sensor making use of CCG in the range of 30 °C to 900 °C is proposed and its response is simulated for the above temperature range. The simulated results have been experimentally verified and were found to be in close agreement with each other. The sensitivity of the proposed sensor is found to be within the bandwidth of the inexpensive spectral sources. By using FBG on sapphire fiber [13] (melting point 2050 °C) in place of silica fiber, high temperatures above 1500 °C can be measured.

Acknowledgement – The authors thank Prof. John Canning for providing the chemical composition gratings which are used in this experimental work.

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Received April 26, 2009
in revised form October 14, 2009