Enhancing the temperature sensitivity of fiber Bragg grating sensor using bimetallic strip

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ABSTRACT

This paper presents theoretical and experimental results carried out on a simple structure based on bimetallic cantilever to enhance temperature sensitivity of fiber Bragg grating (FBG) sensors. Two metals of equal length and width but having different coefficients of thermal expansion (CTE) are bonded with electric arc welding to form the bimetallic strip and FBG was longitudinally affixed to that metallic strip having larger coefficient of thermal expansion. It was observed that the temperature sensitivity of the proposed FBG sensor has increased 5 times more compared to the bare FBG sensor. Moreover, the proposed sensor showed excellent linearity, reversibility, and repeatability.

Keywords: Fiber Bragg grating, bimetallic strip, Temperature measurement, FBG-Bonded

1. INTRODUCTION

Over the last two decades, optical fiber sensors have seen an increased acceptance as well as widespread use for structural sensing and monitoring applications in civil engineering, aerospace, marine, oil & gas, composites and smart structures [1-2]. Optical fiber sensor operation and instrumentation have become well understood and well developed. FBG sensors key research areas include FBG fabrication, FBG demodulation and practical applications [3-5]. Optical fiber sensors, especially FBGs, show distinguishing advantages like immunity to electromagnetic interference and power fluctuations along the optical path, high precision, durability, compact size, ease of multiplexing a large number of sensors along a single fiber, resistance to corrosion, reduced cable dimensions and so on [6-8]. FBGs have become the most prominent sensors and are being increasingly accepted by engineers, as they are particularly attractive to perform strain and temperature measurements under harsh environment areas, like in the presence of electrical noise, EM interference and mechanical vibrations, where conventional sensors cannot operate.

Low-temperature FBG sensors have potential applications in the temperature monitoring of Superconducting magnet support structures where electric sparks are prohibited or electric current is susceptible to high field and radiation; in spacecrafts which use liquid hydrogen-oxygen rocket engines whose parts are exposed to low temperatures, in the storage or transport vessels for cryogens or liquid hydrogen fuel tanks and also in particle physics experiments [9-10].However, the temperature sensitivity of bare FBG is too low to be applied practically. Enhancing the temperature sensitivity of a FBG is very much significant not only for temperature sensing but also for the ever expanding use of FBGs in sensing applications [11-13].

This paper proposes an FBG sensor head designed to enhance the temperature sensitivity based on the strain produced due to differential expansion of dissimilar materials used for bimetallic strip. An increase of sensitivity of 5 times compared to bare FBG sensor has been noticed in the temperature range 123 K to 343 K along with good linearity and repeatability with the proposed sensor head.

2. THEORY

When light from a broad band source illuminates the FBG, the wavelength λ_B of the Bragg reflected peak can be expressed as [14]

$$\lambda_B = 2\, n_{eff} \Lambda \tag{1}$$

Where n_{eff} is the effective refractive index of the FBG and Λ is its period.

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For a bare FBG, the shift of center wavelength $\Delta\lambda_B$ caused by the variation of ΔT can be expressed as [15]

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \zeta)\Delta T = K_T\Delta T \tag{2}$$

Where α *is* the thermal expansion coefficient of the fiber, $\zeta = \frac{1}{n_{eff}}\frac{dn_{eff}}{dT}$ and K_T is the temperature sensitivity coefficient of the bare FBG.

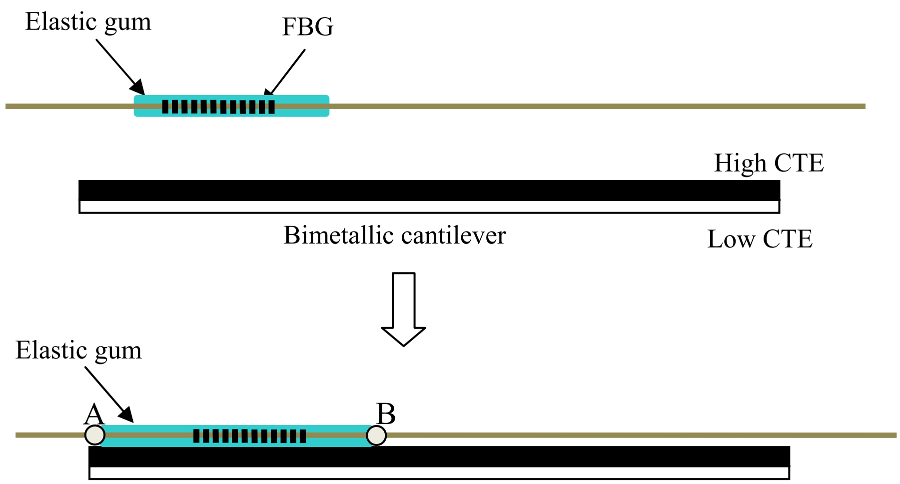

Figure 1. Packaging procedure of sensor head

In order to refrain the grating from chirp, the FBG is coated with a special elastic gum over the grating region in advance [16]. Then the FBG is glued between points A and B on the bimetallic strip longitudinally on the metal having high CTE with cynoacrylate adhesive as shown in fig.1.

When the bare FBG is attached to a substrate whose thermal expansion coefficient is different from it as shown in Fig.1, the shift of the FBG center wavelength with the variation of temperature can be rewritten as

$$\frac{\Delta\lambda_B}{\lambda_B} = [\alpha + \zeta + (1 - p_e)(\alpha_{sub} - \alpha)]\Delta T \tag{3}$$

$$\frac{\Delta\lambda_B}{\lambda_B} = [K_T + (\alpha_{sub} - \alpha)K_\varepsilon]\Delta T \tag{4}$$

Where α_{sub} is the thermal expansion coefficient of the substrate material, $K_\varepsilon = 1 - p_e$ is the strain-tuning coefficient, and p_e is the effective photoelastic coefficient. For a conventional fiber, $\alpha \cong 0.55 \times 10^{-6}$ /°C, $\zeta \cong 7 \times 10^{-6}$ /°C, $p_e \cong 0.22$.

If the FBG is bonded along the center of the bimetallic strip, whose expansion coefficient is larger than that of the other, the difference in thermal expansion coefficients of the materials lead to the bending of the strip, further contributing to the shift of the center wavelength of the FBG. Therefore, Eqn. (4) should be rewritten as [17]

$$\frac{\Delta\lambda_B}{\lambda_B} = [K_T + (\alpha_{sub} - \alpha)K_\varepsilon + \alpha K_\varepsilon(\alpha_{sub} - \alpha_1)]\Delta T \tag{5}$$

$$\frac{\Delta\lambda_B}{\lambda_B} = [K_T + (\alpha_{sub} - \alpha)K_\varepsilon + K]\Delta T, \tag{6}$$

Where $K = \alpha K_\varepsilon(\alpha_{sub} - \alpha_1)$ is the enhancement in temperature sensitivity coefficient that results from the strain of the bimetallic strips, $\alpha = [LBh^2E_lE_{sub}]/\{4I[(E_l + E_{sub})^2 + 12E_lE_{sub}]\}$ where E, L, B, *h*, I and α are young's modulus, length, width, thickness, moment of inertia, and thermal expansion coefficient, respectively. Subscript

“l” indicates the sheet whose expansion coefficient is smaller, and subscript “sub” indicates the sheet whose expansion coefficient is larger. To increase K, the difference in the expansion coefficients of the strips should be increased. In proposed sensor, the bimetallic strip was made up of brass and steel, whose expansion coefficients are 19×10^{-6} /℃ and 13×10^{-6} /℃ respectively.

3. EXPERIMENTAL SETUP AND DISCUSSION

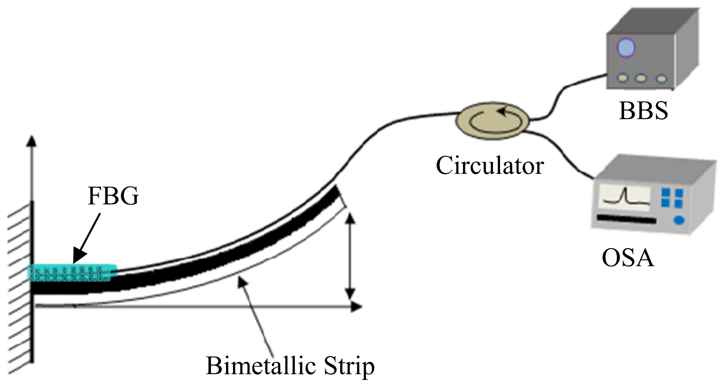

Figure 2. Experimental setup for the temperature response of proposed bimetallic FBG sensor in Low temperatures

The required FBG of length 2 cm having Bragg reflected peak of 1550.696nm at temperature 30 ^{o}C is written in photosensitive fiber with 248 nm UV laser assisted grating writing facility at CSIO, Chandigarh using phase mask technique. A bimetallic strip of length 6.6 cm and width 0.35 cm; with thicknesses of Brass and steel as 0.075cm , 0.041cm respectively has been employed for the fabrication of the sensor head. The bare FBG is glued to the surface of the brass strip longitudinally using cynoacrylate adhesive.

The Bimetallic strip will be straight at some reference temperature. If the temperature is hotter than the reference , brass expands more and its greater length puts it on the outside of the curve while brass contracts more and its shorter length puts it on the inside of the curve if the temperature is cooler than the reference .

Fig.2 shows the experimental setup consisting of broadband source (BBS) with 40 nm spectral width (1525-1565 nm), connected to port-1 of 3-port fiber optic circulator, which is used to launch light into the grating inscribed fiber that is connected to port-2 of the circulator. The back reflected wavelength shifts were monitored by an optical spectrum analyzer (86142B, Agilent Inc.) via port-3.

The experiment consists of placing the sensor head in the cryogenic chamber whose temperature can be varied with an accuracy of ±1^{o}C. The sensor is cooled with LN2 fumes down to123 K from room temperature and the Bragg reflected wavelength is noted. During the process of cooling down from room temperature, each sampling temperature was stabilized at least 5 min before the wavelength shift is noted. The corresponding temperature response of the bare FBG has also been noted separately for the above temperature range.

Fig.3 shows the plot of the temperature response of bare FBG. Its sensitivity $\left(\frac{d\lambda_B}{dT} = 7.31 \text{ pm/°C}\right)$is found very low compared to that of $\left(\frac{d\lambda_B}{dT} = 35.57 \text{ pm/°C}\right)$ the proposed sensor head with FBG on bimetallic strip shown in Fig.4; and is found 5 times more than that of bare FBG. The theoretical simulation results carried out with Eqn.(6) using MATLAB are also very closely matching with the experimental results. The reasons for the enhancement of temperature sensitivity can be attributed to the contribution of additional coefficients $(\alpha_{sub} - \alpha)K_\varepsilon$ and $\alpha K_\varepsilon(\alpha_{sub} - \alpha_1)$.

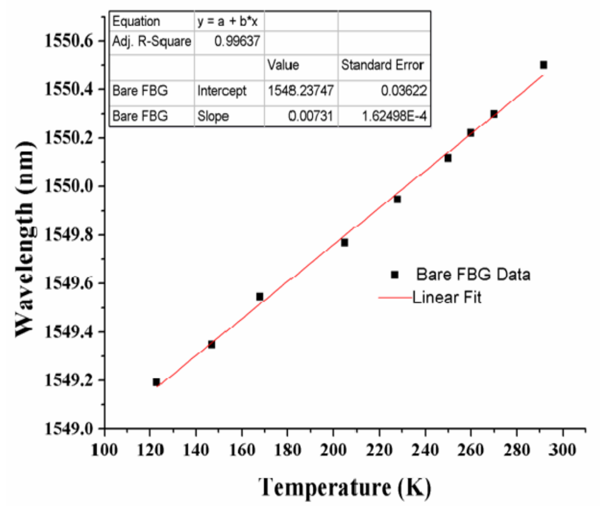

Figure 3. Temperature response of Bare FBG from 123 K to room temperature

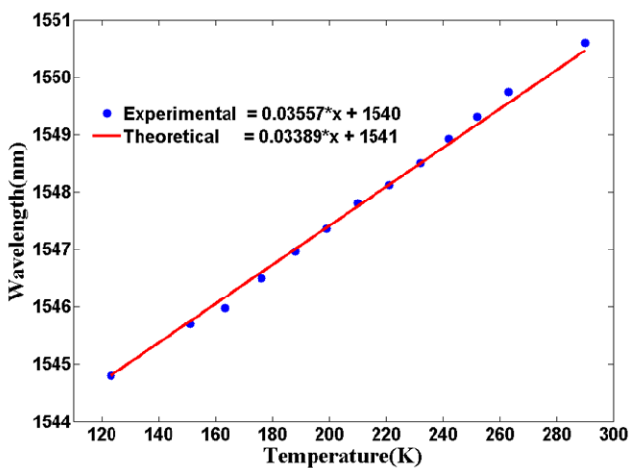

Figure 4. Temperature response of the proposed sensor from 123 K to room temperature

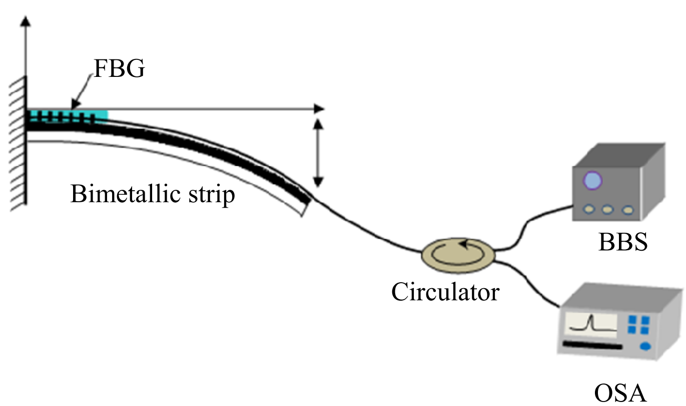

Figure 5. Experimental setup for the temperature response of proposed bimetallic

Fig.5 illustrates the experimental setup for measurements above room temperatures. The same sensor head is placed in a high temperature chamber whose temperature can be varied with an accuracy of ±1°C, and the wavelength of the reflected Bragg peak is monitored from Room temperature to 70 °C. During the process of heating from Room temperature also, each sampling temperature was stabilized at least 5 min before the wavelength shift is noted. The corresponding temperature response of the bare FBG has also been noted separately for the above temperature range.

Figure 6 illustrates the temperature dependence of the measured wavelength shift for the bare FBG, giving a temperature sensitivity $\left(\frac{d\lambda_B}{dT} = 14.1 \text{ pm/°C}\right)$ which is very less compared to the sensitivity $\left(\frac{d\lambda_B}{dT} = 71.01 \text{ pm/°C}\right)$ obtained from the temperature response of the proposed sensor head with FBG on bimetallic strip shown in Fig.7. The temperature sensitivity in this case also is found 5 times more than that of bare FBG. The experimental data and the simulated results are closely matching at all points of measurement with a linearity of 99.8%.

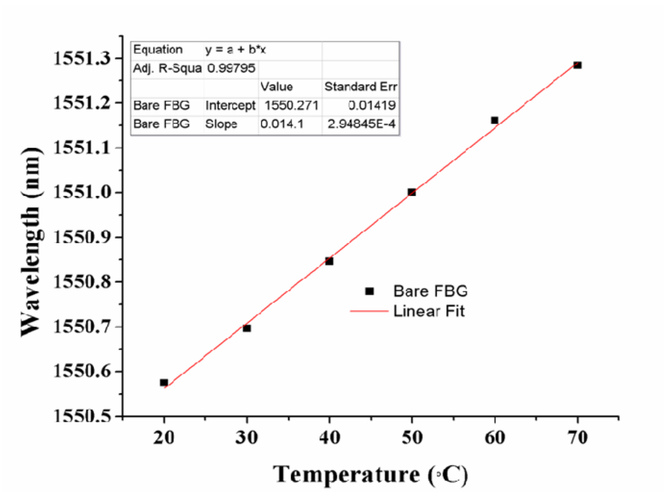

Figure 6. Temperature response of Bare FBG from room temperature to 70 °C

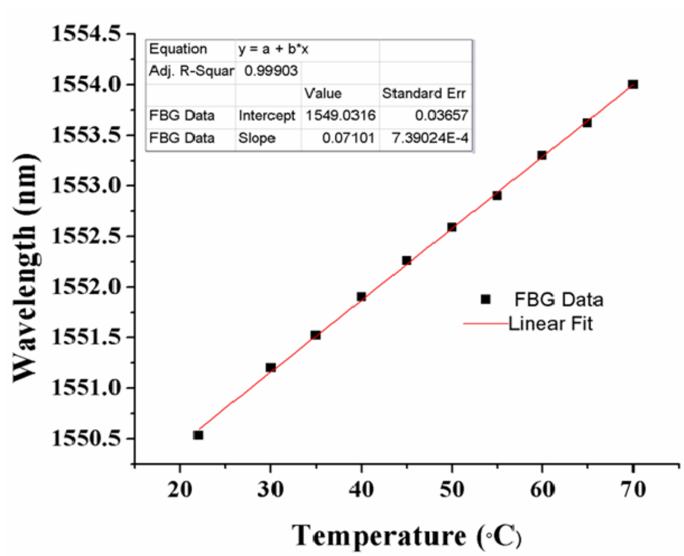

Figure 7. Temperature response of proposed sensor head from room temperature to 70 °C

4. CONCLUSIONS

A simple sensor head for enhancing the temperature sensitivity has been proposed with FBG attached to a bimetallic strip. The theoretical and experimental results on the sensor reveal that the temperature sensitivity of the FBG can be significantly increased by the proposed configuration.

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