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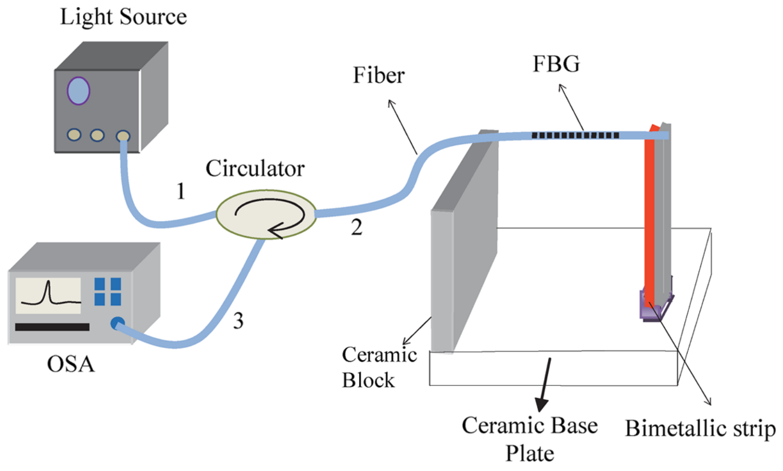

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Method for Enhancing and Controlling Temperature Sensitivity of Fiber Bragg Grating Sensor Based on Two Bimetallic Strips

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Abstract: This paper presents a novel structure based on bimetallic strips for enhancing temperature sensitivity of fiber Bragg grating (FBG) sensors. Two different types of sensor heads have been designed for this implementation. The first sensor head consists of an FBG that is fixed between ceramic block on one side and a bimetallic strip made up of aluminum and copper on the other. The second sensor head consists of an FBG that is fixed between two bimetallic strips. Theoretical and experimental studies carried out on these proposed sensor heads resulted in an increase in temperature sensitivity of about six times greater than that of bare FBG sensor. Further, the proposed sensors have shown good linearity and stability.

Index Terms: Fiber Bragg Gratings, bimetallic strips, temperature sensitivity, controllability, thermal stability.

1. Introduction

Over the last two decades, optical fiber sensors have seen an increased acceptance as well as widespread use in scientific research and in diversified engineering applications [1], [2]. Optical fiber sensors, especially fiber Bragg gratings (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 [3]–[8]. FBGs, therefore, have become the most prominent sensors and are being increasingly accepted by engineers, as they are particularly attractive to perform measurements under harsh environment areas, like the presence of electrical noise, EM interference and mechanical vibrations, where conventional sensors cannot operate.

In recent years, various FBG sensors have constantly been developed and their uses have expanded rapidly into such applied fields as the measurement of strain, displacement, torsion angle, torque, electric current, and gas traces. Moreover, FBGs can also be used to sense temperature, but the temperature sensitivity of bare FBG sensor is only approximately 0.01 nm/°C, which is too low to be applied practically. Enhancing the temperature sensitivity of FBG is significant not only for temperature sensing but also for their expanding sensing applications. It is therefore necessary to design suitable sensor structures that provide high temperature sensitivity along with good linearity and stability [9]. Also, many encapsulation methods for enhancing the temperature sensitivity of FBGs have been put forward [10]–[12].

This paper proposes two FBG sensor heads 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 about 6 times more compared to bare FBG sensor has been noticed in the temperature range from room temperature to 100 °C along with good linearity and repeatability with the proposed sensor heads. Further, the sensitivity can also be controlled by changing the lengths of the bimetallic strips; it is seen that increase in the lengths enhanced the sensitivity while decreased lengths result in a decrease in sensitivity.

2. Theory

For a uniform FBG, both the temperature and strain dependences are linear, and hence, in principle, the strain response of FBG arises due to both the physical elongation of the grating corresponding fractional change in grating pitch, thereby causing a change in fiber index due to photoelastic effects; as well as on the thermal response of the grating that arises due to the inherent thermal expansion of the fiber material and the temperature dependence of the refractive index. Therefore, the relative change in Bragg wavelength with strain and temperature can be expressed as [13], [14]

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - p_e)\varepsilon + (\alpha_s + \zeta_s)\Delta T \tag{1}$$

$$\Delta\lambda_B = [(1 - p_e)\varepsilon + (\alpha_s + \zeta_s)\Delta T]\lambda_B \tag{2}$$

where ε is the axially applied strain, p_e is the effective photoelastic constant ($\sim$0.22) of the fiber material, ΔT is the temperature change, α_s and ζ_s are the thermal expansion ($\sim 5 \times 10^{-7}$ K^{-1}) and thermooptic ($\sim 7 \times 10^{-6}$ K^{-1}) coefficients of the fiber material, respectively.

Bimetallic strip (consisting of aluminum and copper) will normally be made straight at some reference temperature. If the temperature is hotter than the reference, aluminum expands more and its greater length puts it on the outside of the curve while aluminum contracts more and its shorter length puts it on the inside of the curve if the temperature is cooler than the reference [15].

A bimetallic strip consisting of two metallic components thus alters its curvature according to the (3) given below when subjected to heat, owing to difference in thermal expansions of the two constituent materials used (16)

$$\frac{1}{R_T} - \frac{1}{R_0} = \frac{6(\alpha_2 - \alpha_1)(1 + m)^2}{3(1 + m)^2 + (1 + m \times n)\left(m^2 + \frac{1}{m \times n}\right)} \times \frac{T - T_0}{s} \tag{3}$$

where R_T = Radius at temperature T, R_0 = Radius at temperature T_0, $m = s_1/s_2$ where s_1 and s_2 are thicknesses of the component alloys, $s = s_1 + s_2$ and $n = E_1/E_2$ where E_1 and E_2 are the module of elasticity and α_1 and α_2 are the coefficients of linear thermal expansion of component alloys, respectively. If

$$k = \frac{6(\alpha_2 - \alpha_1)(1 + m)^2}{3(1 + m)^2 + (1 + m \times n)\left(m^2 + \frac{1}{m \times n}\right)} \tag{4}$$

where, the constant k is known as flexivity or Specific curvature, then

$$\frac{1}{R_T} - \frac{1}{R_0} = k \times \frac{T - T_0}{s} \tag{5}$$

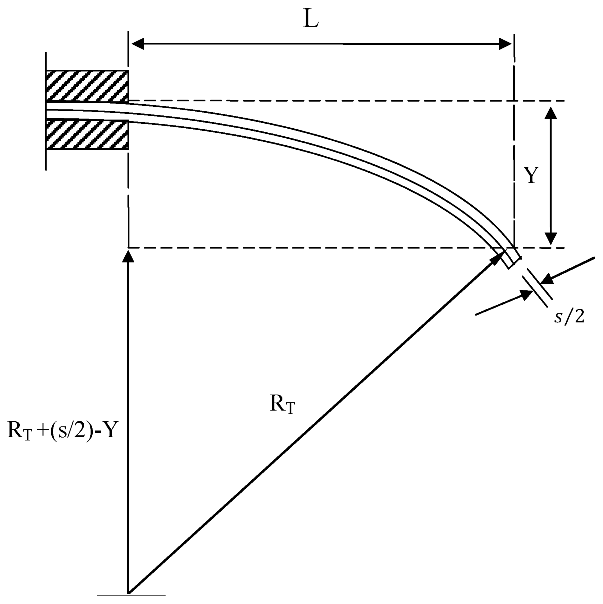


Fig. 1. Deflection of bimetallic cantilever strip.

and therefore

$$k = \frac{\left(\frac{1}{R_T} - \frac{1}{R_0}\right)s}{T - T_0}. \tag{6}$$

The Specific curvature can be defined as "the change of curvature of a bimetal strip per unit temperature change time's thickness" in the absence of external forces. If the strip is flat to start with, $R_0 = \infty$, and the (3) can be simplified to

$$\frac{1}{R_T} = k \times \frac{T - T_0}{s}. \tag{7}$$

This causes the free end of the cantilever getting deflected by an amount Y, as shown in Fig. 1. From the figure, we obtain

$$\left(R_T + \frac{s}{2}\right)^2 = \left(R_T + \frac{s}{2} - Y\right)^2 + (L)^2 \tag{8}$$

$$\frac{1}{R_T} = \frac{2Y}{L^2 + Y^2 - Y \times s}. \tag{9}$$

Since $Y \times s$ is very small, it can be neglected in the denominator. Therefore, (9) becomes

$$\frac{1}{R_T} = \frac{2Y}{L^2 + Y^2}.$$

And since $L \gg Y$, Y^2 will be very small and neglecting its effect, we can write

$$\frac{1}{R_T} = \frac{2Y}{L^2}. \tag{10}$$

Now, by solving (7) and (10), we obtain

$$Y = \frac{(T - T_0)L^2}{2.s} \times k \tag{11}$$

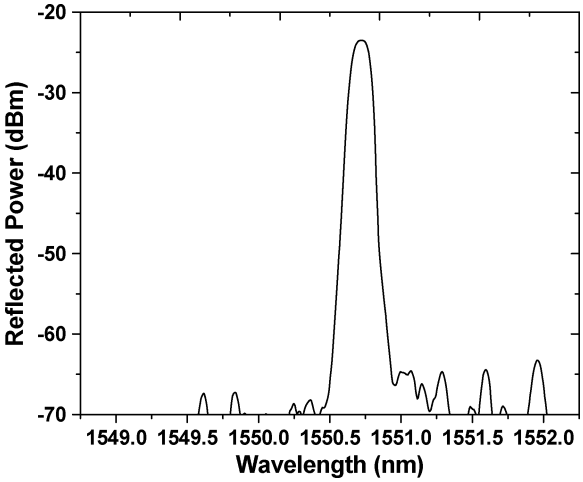


Fig. 2. Reflected spectra of FBG.

where Y is the deflection produced at the free end of the bimetallic strip of length L. Due to this deflection, the grating will be subjected to an average strain given by

$$\varepsilon = \frac{Y}{L}. \tag{12}$$

From (11) and (12), we get

$$\varepsilon = \frac{1}{L}\frac{(T - T_0)L^2}{2.s} \times k. \tag{13}$$

And substituting (13) in (2) we obtain

$$\Delta\lambda_{B1} = \left[\left((1 - p_s)\frac{1}{L}\frac{(T - T_0)L^2}{2.s} \times k\right) + (\alpha_s + \zeta_s)\Delta T\right]\lambda_B. \tag{14}$$

This is the equation for the total Bragg wavelength shift when the FBG, fixed between a ceramic block and single bimetallic strip, is subjected to a temperature change, as shown in Fig. 3.

In case the FBG is fixed between two bimetallic strips as shown in Fig. 4, the total Bragg wavelength shift is given by

$$\Delta\lambda_{B2} = \left[2 \times \left((1 - p_s)\frac{1}{L}\frac{(T - T_0)L^2}{2.s} \times k\right) + (\alpha_s + \zeta_s)\Delta T\right]\lambda_B. \tag{15}$$

2.1. Sensor Head Fabrication

The required FBG of length 2 cm, with Bragg reflected peak at 1550.7 nm and having bandwidth of 0.102 nm at temperature 30 °C, is written in photosensitive fiber with 248 nm UV laser assisted grating writing facility at CSIO, Chandigarh using phase mask technique. The reflection spectra of the grating are as shown in Fig. 2.

Bimetallic strip of length 32 mm and width 4.6 mm, with thicknesses of copper and aluminum as 0.023 mm, 0.85 mm, respectively has been employed for the fabrication of the two sensor heads. The two proposed sensor heads; the first one consisting of bare FBG glued between the surfaces of the bimetallic strip and ceramic block; and the second one with the bare FBG glued between two bimetallic strips, using cynoacrylate adhesive, are shown in Figs. 3 and 4, respectively. The separation between the bimetallic strip and ceramic block or between the two bimetallic strips used in this sensor head is 4 cm (2 cm length of the FBG + 1 cm each on either side of it).

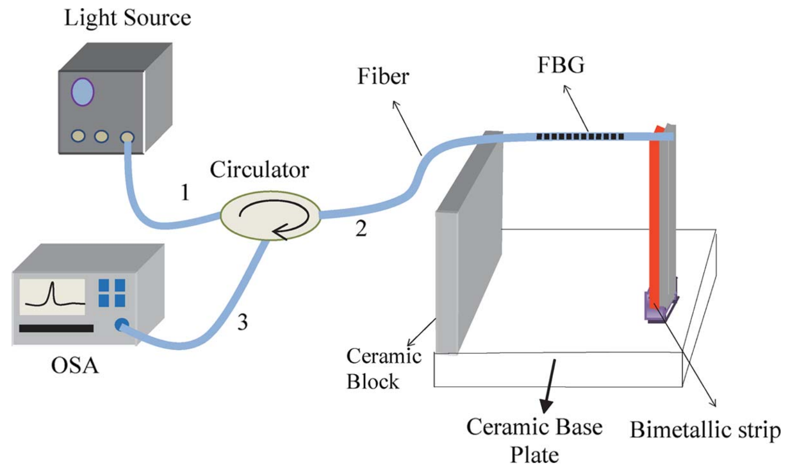


Fig. 3. FBG fixed between metal block and one bimetallic strip.

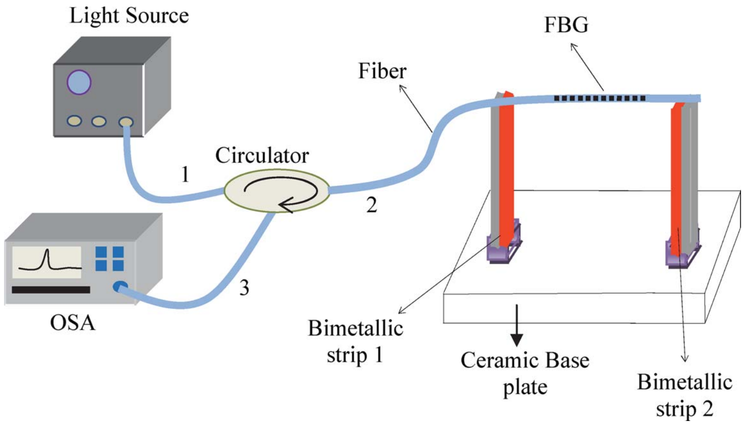


Fig. 4. FBG fixed between two bimetallic strips.

3. Experimental Setup and Discussion

The experimental setup consisting of a broadband source (BBS) with 40 nm spectral width (1525–1565 nm), connected to port-1 of a 3-port fiber optic circulator, 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, as shown in Figs. 3 and 4.

The experiment consists of placing the sensor heads in the hot chamber whose temperature can be varied with an accuracy of ±1 °C. The sensor is heated from room temperature to 100 °C and the Bragg reflected wavelength is noted. During the process of heating from room temperature to 100 °C, each sampling temperature was stabilized at least 10 minutes 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. 5 shows the plot of the temperature response of bare FBG and the two proposed FBG sensor heads. The sensitivity of bare FBG ($d\lambda_B/dT = 11$ pm/°C) is found to be very low compared to that of ($d\lambda_B/dT = 32$ pm/°C) the proposed first and ($d\lambda_B/dT = 64$ pm/°C) second sensors heads as shown in Fig. 5. The sensitivity is also found three times more than that of bare FBG in case of first sensor head and six times more than that of bare FBG with the second sensor head.

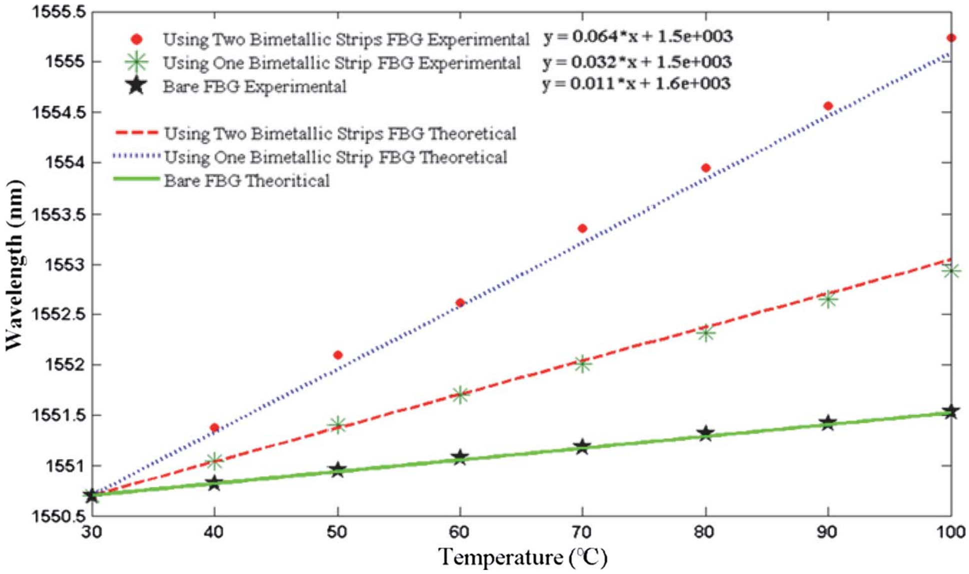
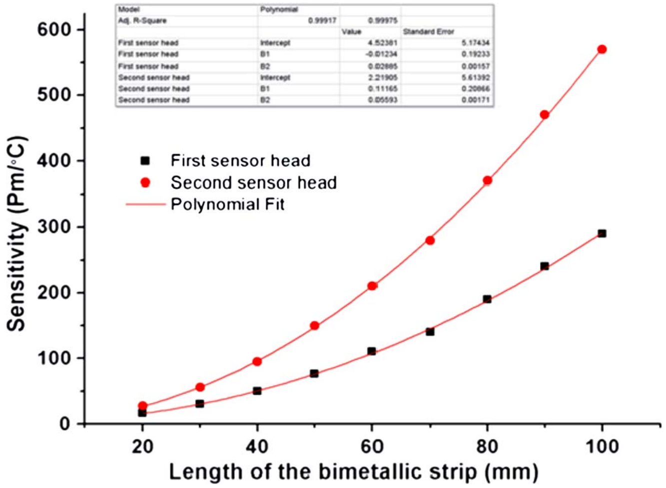


Fig. 5. Experimental and theoretical measured wavelength versus temperature.



Model	Polynomial		
Adj. R-Square	0.99917	0.99975	
		Value	Standard Error
First sensor head	Intercept	4.52381	5.17434
First sensor head	B1	-0.01234	0.19233
First sensor head	B2	0.02885	0.00157
Second sensor head	Intercept	2.21905	5.61392
Second sensor head	B1	0.11165	0.20866
Second sensor head	B2	0.05593	0.00171

Fig. 6. Increase in sensitivity with increase in length of bimetallic strips.

An advantage of these sensor heads is that the sensitivity is controlled by changing the lengths of bimetallic strips. Further, theoretical simulation results carried out with (14) and (15) using MATLAB are also very closely agreeing with the experimental results. The reasons for the enhancement of temperature sensitivity can be attributed to the contribution of additional coefficient

$$\frac{1}{L}\frac{(T-T_0)L^2}{2.s}\times k.$$

An advantage of these sensor heads is that the sensitivity is controllable by changing the lengths of bimetallic strips. Fig. 6 represents the second order polynomial fit for the simulated results of increase in sensitivity with increase in length of the bimetallic strips.

4. Conclusion

A novel structure for enhancing and controlling temperature sensitivity has been designed based on two sensor heads. The theoretical and experimental results show that the temperature sensitivity of the FBG can be greatly enhanced and controlled together with good linearity, stability and repeatability by using the bimetallic strips.

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