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New Compensation Method for Temperature Sensitivity of Fiber Bragg Grating Using Bi-metal

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A new method for temperature compensation of fiber Bragg grating (FBG) using bi-metal is proposed and experimentally demonstrated. Bi-metal bends toward the metal of low temperature expansion coefficient as the temperature increases, and this property is utilized to cancel the thermo-optic effect of the fiber. The optimum thickness of the high coefficient metal was empirically found by the trial-and-error method. The temperature sensitivities were 8.1 pm/°C and −0.018 pm/°C for the uncompensated and compensated FBGs, respectively, which indicates a reduction to a mere 0.22 % of the original sensitivity. No appreciable change in the spectral shape was observed. The packaging technique described in this paper is simple and compact, and it can be used for FBGs in WDM and DWDM communication systems that have stringent requirements on the temperature stability of the components.

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I. INTRODUCTION

Fiber Bragg gratings (FBGs), which have periodic perturbation of the refractive index along the fiber length, have attracted much attention because they have the characteristics of narrow bandwidth and high reflectivity and can be applied to various important components in wavelength division multiplexed (WDM) system, such as narrow bandwidth transmission (reflection) filter, add/drop multiplexer, and tunable fiber laser. They are also used in applications like routing, filtering, control, and amplification of optical signals in high-capacity WDM telecommunication networks. [1]

In order for the FBGs to be widely used in WDM communication systems, it is imperative that the spectral characteristics be stabilized against the effect of the external environment like the temperature. The temperature sensitivity of the FBGs is typically in the range of ~1 nm/100 °C, which is too large for communication applications because the channel spacing in WDM systems is 0.8 nm or even less for DWDM systems. The operating temperature span is usually taken to be around 100 °C. If the wavelength shift due to the temperature variation in this range is to be a small fraction of the channel spacing, the temperature sensitivity needs to be reduced to the order of 0.1 pm/°C. In case of FBGs, such stringent requirements on the temperature sensitivity can only be met by using proper packaging techniques. [2]

In general, the packaging techniques for compensation of the temperature sensitivity can be divided into two categories. In both types of packaging techniques, the intrinsic positive temperature sensitivity of the FBG is cancelled by the contraction of the packaging that embeds the FBG. In one method, materials with negative thermal expansion coefficient, e.g., liquid crystalline polymers (LCP), are used. [3] The other method utilizes a combination of two materials with different thermal expansion coefficients. [4] In this method, the ends of the fiber section incorporating the FBG are attached to the materials with different thermal expansion coefficients relative to one another. The fiber may be in a pre-tension state so as to prevent loss of tension as temperature increases.

In this paper, we will discuss a novel method of compensation for the temperature sensitivity of FBGs using bi-metal made of thin rectangular plates of two materials with different thermal expansion coefficients attached together. The FBG is then attached to the surface of the bi-metal such that thermally induced bending of the bi-metal causes contraction of the fiber, which effectively cancels the positive temperature sensitivity of the FBG. In a sense, this new method can be considered a combination of the two methods mentioned above. Two materials of different thermal expansions coefficients are used in such a way that the bi-metal as a piece introduces a negative thermal expansion coefficient. This simple technique will permit compact and inexpensive packaging for temperature compensation of FBGs.

II. THEORY

The FBG is a wavelength-selective reflective filter and the resonance wavelength is determined by the effective refractive index of the core mode and the periodicity of the grating. The resonance wavelength λ_B satisfies the condition

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

where n_{eff} is the effective refractive index of the core mode and Λ is the periodicity of the grating. In the absence of the externally applied strain other than packaging, the shift of the resonance wavelength is caused by the changes of the grating period Λ and the effective index n_{eff} due to the thermal effect. In this case, the resonance wavelength shift of FBG due to the thermal effect can be written as [5,6]

$$\Delta\lambda_B = \lambda_B(\alpha + \alpha' + \kappa)\Delta T, \tag{2}$$

where $\alpha = (1/\Lambda)(\partial\Lambda/\partial T)$ is the thermal expansion coefficient of the fiber and $\kappa = (1/n_{eff})(\partial n_{eff}/\partial T)$ is the thermo-optic coefficient. α' represents the thermal expansion or contraction provided by the packaging. Usually, the thermo-optic effect gives the dominant contribution to the wavelength shift in FBG, i.e., $\alpha \ll \kappa$. From Eq. (2), the wavelength shift can be nulled by setting α' such that

$$\alpha + \alpha' + \kappa = 0. \tag{3}$$

All of the known techniques for temperature compensation of FBG are based on Eq. (3), and for $\kappa > 0$, the packaging is designed such that the fiber is contracted as the temperature increases. In Ref. 7, it has been reported that the Bragg wavelength of FBG written on D-type fiber is shifted as the fiber is bent. Due to the asymmetry of the fiber geometry, the grating period and the resonance wavelength will decrease if the direction of the curvature is inward normal to the flat surface of the D-type fiber, and they will increase otherwise. This result indicates that it is possible to control the resonance wavelength shift of FBG by attaching it to a rod or a cantilever and bending it in a particular direction. [8,9] Temperature compensation of FBG can be done using the same principle by using a bi-metal, which is composed of two metals with different thermal expansion coefficients. Let L be the metal with lower thermal expansion coefficient and let H be the metal with higher thermal expansion coefficient. The bi-metal will bend toward L when the temperature is increased and will bend toward H when the temperature is decreased as shown in Fig. 1. With $\kappa > 0$, if the FBG is attached to the bi-metal on the side of L, this setup effectively provides the negative thermal expansion coefficient α' and the positive temperature sensitivity κ will be partially cancelled.

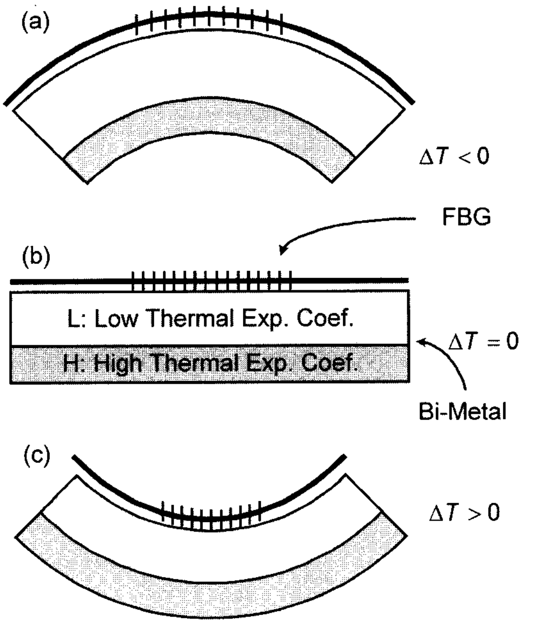

FIG. 1. Bending of the bi-metal under the temperature change (a) $\Delta T < 0$, (b) $\Delta T = 0$, and (c) $\Delta T > 0$. Bi-metal bends toward the low coefficient metal when the temperature is increased.

Let α_L and α_H be the thermal expansion coefficients of the metals L and H and let t_L and t_H be the thickness. Then the strain on the FBG due to the bi-metal can be shown to be

$$\frac{\Delta L}{L} = \alpha'\Delta T = \left(\alpha_L - \frac{\alpha_H - \alpha_L}{1 + t_H/t_L}\right)\Delta T, \tag{4}$$

in which case the radius of curvature of the bi-metal at the interface between the two metals is

$$R = \frac{t_L}{2}\left\{1 + \frac{1 + \alpha_L\Delta T}{\Delta T}\frac{1}{\alpha_H - \alpha_L}\left(1 + \frac{t_H}{t_L}\right)\right\}. \tag{5}$$

Since the bending of the bi-metal depends on relative thickness of the two metals, nearly complete cancellation is possible if the thicknesses of the two metals L and H are properly adjusted. From Eqs. (3) and (4), the thickness ratio should be

$$\frac{t_H}{t_L} = \frac{\alpha_H - \alpha_L}{\alpha_L + \kappa + \alpha} - 1 \tag{6}$$

for compensation of the temperature sensitivity. In Eq. (6), $\kappa + \alpha$ is the relative temperature sensitivity $\Delta\lambda_B/(\lambda_B\Delta T)$ of the FBG before compensation.

III. EXPERIMENTS AND RESULTS

For demonstration of the temperature compensation of FBG using bi-metal as explained in the previous section, we procured and disassembled a commercially available thermostat. The bi-metal originally coiled in the thermostat was unwound carefully into the shape of a rectangular parallelepiped. The dimension of the bi-metal was approximately L×W×H = 7 cm× 1 cm ×1 mm. The initial measurement of the temperature sensitivity of the FBG using the unmodified bi-metal gave negative temperature sensitivity, which indicated that the thickness of H was too large. Without the data on the temperature expansion coefficients of the two metals L and H available, the proper thickness of H that nearly cancels the positive temperature sensitivity of FBG was found empirically by making several measurements of the net temperature sensitivity while gradually reducing the thickness of H using a file and fine sandpaper. The thickness of L was kept unchanged during this process. At the end of this process, the thickness ratio between H and L was approximately 2:5.

The setup for holding the bi-metal with the FBG attached on the side of L (bottom) is illustrated in Fig. 2. A similar setup with the bi-metal standing straight was also tried for fear of the gravity effect. However, the difference in the result was negligible. Fig. 3 shows the experimental setup for measurement of the temperature sensitivity. The setup shown in Fig. 2 was put in the temperature-controlled dry oven and the transmission spectra were measured using an optical spectral analyzer (OSA) while monitoring the temperature inside the oven. The initial temperature in the oven was set to below 0 °C using dry ice, and then the temperature was increased slowly at the rate of ~1 °C/min by heating. The measurements were done for the temperature in the range between 0 °C and 100 °C. As for the measurement setup on OSA, the resolution was 0.08 nm, the wavelength span was 5 nm, and the sensitivity was −85 dBm.

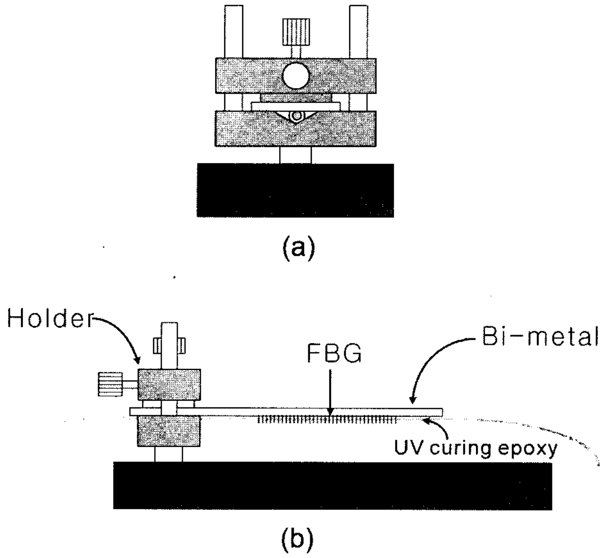

FIG. 2. The setup for holding the bi-metal with the FBG attached to the surface: (a) the side view and (b) the front view.

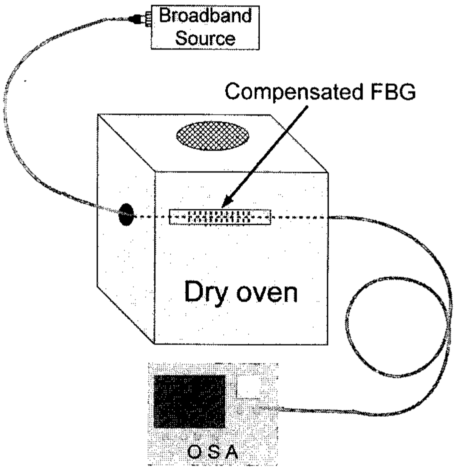

FIG. 3. The setup for measurement of the temperature sensitivity of the FBG in a temperature-controlled dry oven.

The FBGs were fabricated using photosensitivity fibers made at K-JIST, which were loaded with hydrogen at 80 bars and 100 °C for 7 days. We used the phase mask and KrF excimer laser to for inscription of the FBG. The specifications of the fiber are: cutoff wavelength λ_c = 1002 nm, Δ = 1.1 %, NA = 0.22, core and cladding diameters 3.6μm and 125μm, respectively. The length of the FBG was 2 cm, the Bragg wavelength was measured to be 1536 nm, the bandwidth was 0.44 nm, and the peak depth was 29 dB. The output energy of the KrF laser was 160 mJ/Pulse, the period of the phase mask was 1060 nm, and the UV exposure time was about 3 minutes.

Figs. 4(a) and (b) show the transmission spectra of the FBG with and without temperature compensation, respectively, in the temperature range of 0 to 100 °C. The shift of the resonance wavelength with temperature is seen in Fig. 5 for both the compensated and uncompensated cases. The temperature sensitivity of the uncompensated FBG is about 8.1 pm/°C. In contrast, it is clear from Fig. 4(b) that there is virtually no shift of the resonance wavelength for the temperature-compensated case. It is also seen that the spectral shape is well preserved. The total shift as the temperature is increased from 0°C to 100°C

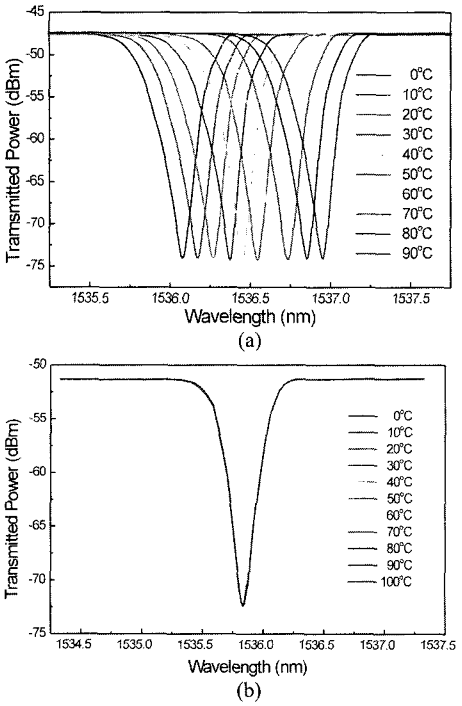

FIG. 4. Shift of the transmission spectra of FBG under the change of temperature in the range of 0 °C to 100 °C: (a) uncompensated FBG and (b) compensated FBG.

is approximately −1.8 pm, which corresponds to the temperature sensitivity of −0.018 pm/°C. The negative net temperature sensitivity indicates that the wavelength shift due to the thermo-optic effect was actually overcompensated by a small amount. This value is 450 times smaller than the uncompensated data and it is merely 0.22 % of the original sensitivity. Even for the channel spacing of 0.2 nm in DWDM systems, the maximum wavelength shift in the 100°C temperature span will be less than 1 % of the channel spacing. The resonance wavelength shift due to the hysteresis effect of the bi-metal when cycled over 40 °C range was approximately 0.1 pm, which is negligibly small considering the residual temperature sensitivity of −0.018 pm/°C after compensation.

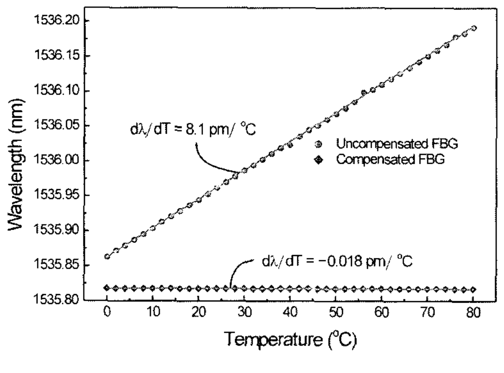

FIG. 5. Shift of the resonance wavelength of FBG for the uncompensated and compensated cases. The temperature sensitivity of the compensated FBG is only 0.22 % of the uncompensated FBG.

IV. CONCLUSION

A new method for temperature compensation of FBG using bi-metal was proposed and experimentally demonstrated. We used the characteristic that bi-metal bends toward the low coefficient side as the temperature is increased in order to compensate for the positive temperature sensitivity of the resonance wavelength shift in FBG. The optimum thickness of the high coefficient metal was empirically found by the trial-and-error method.

The resonance wavelength shift of FBG is dominated by the thermo-optic effect, and in our experiments, the temperature sensitivity of the uncompensated FBG was 8.1 pm/°C. In contrast, the total wavelength shift of the compensated FBG over the temperature span of 100°C was approximately −1.8 pm, which corresponds to the temperature sensitivity of −0.018 pm/°C and is only 0.22 % of the original sensitivity. We did not observe any appreciable change in the spectral shape. The packaging technique described in this paper is simple and compact, and the measurement data indicates that it can be used in the WDM and DWDM communication systems that have stringent requirement on the temperature stability of the components.

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