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Passive Temperature Compensating Package for Optical Long Period Fiber Gratings

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We present a simple design rule for a passive temperature-compensating optical package. We also present experimentally that a package fabricated by using the design rule compensates the temperature dependence of the resonant wavelength of an optical long period fiber grating by varying the strain inside the fiber. The package fabricated in this work consists of two pieces of brass tube, 10 mm long, and a piece of nylon rod, 45.4 mm long. It is shown that the package can compensate the temperature-induced wavelength shifts of the long period grating to a range of 6.8 pm/°C, compared with 0.048 nm/°C for an uncompensated grating. The reduced strength of the fiber caused by exposure to ultraviolet limits the performance of the package to the range of operating temperature from -3 °C to 70 °C.

I. INTRODUCTION

In lightwave systems, it is sometimes necessary to have wavelength standards, for examples, for different channels of wavelengths-division-multiplexed systems and gain flattening of optical sources, and add/drop couplers [1-3]. Such a device could require a frequency standard or wavelength stability. To achieve the wavelength stability over the range of operating temperatures, Miller and Stultz [1] reduced the sensitivity of a fiber Fabry-Perot filter to less than 0.007 nm/°C over the range of temperature from 23 °C to 72 °C, Yoffe *et al.* [2,3] reduced the sensitivity of the Bragg grating to 0.5 pm°C over the range from -40 °C to 80 °C, and Chen *et al.* [4] reduced the sensitivity of fused couplers to 0.006 nm/ °C over the range from 30 °C to 80 °C.

Both optical fiber Bragg gratings (FBG) [2,3] and optical long period fiber gratings (LPFG) are convenient for these purposes because not only the grating resonance act as a compact, narrow-band tunable filter or reflector but also it can be operated in a wavelength-coding manner. Long period fiber gratings have demonstrated a wide range of applications both in optical communications such as wavelength-division multiplexers (WDMs) [5], gain equalizers [6], bandpass filters [7], polarizers [8,9], and in sensing elements and sensing demodulators [10,12], as well as FBG [13,14]. However, the disadvantage of an optical long period fiber grating is that it is temperature-sensitive due to the inherent thermo-optic coefficient and, to a lesser extent, the thermal expansion of the optical fiber. The operating temperature must thus be controlled in order to maintain the resonant peak wavelength of a grating to be used for the purpose of the wavelength stability. In reality, uncompensated long period gratings exhibit large temperature coefficients of approximately 0.048 nm/°C on the peak wavelength. This can cause a serious problem in optical applications. An alternative approach would build devices that passively compensate the temperature dependence of gratings, so that these devices adjust the amount of strain necessary to cancel the shift in the grating wavelength with changes in temperature due to its physical configuration. Therefore, this scheme may not need any active temperature control. Passive mounts, fabricated by using the design rule employed in this work, compensate temperature dependence of the resonant wavelength of a long period grating by changing the strain inside the fiber. Furthermore, we show that the compact and rugged devices can be simply built and can reduce the temperature-induced wavelength shift of a grating by an order of magnitude for long period gratings.

II. PRINCIPLE OF TEMPERATURE-COMPENSATION FOR A LONG PERIOD GRATING

II. A. Characteristics of a Long Period Grating

The long period gratings used in this work are formed to a Corning FLEXCOR photosensitive fiber by exposure to ultraviolet (UV) light through a laser-machined amplitude mask made of brass thin plate. The phase matching condition between the guided mode and the forward propagating cladding mode is given by

$$\lambda_g^{(m)} = (n_e - n_{cl}^{(m)})\Lambda \tag{1}$$

where Λ is the period of the core refractive index modulation to couple the fundamental mode to the mth-cladding mode [7,12]. In this case, the phase matching vector is short for a long Λ, typically on the order of hundreds of microns. The typical transmitted spectrum of the long period grating of length 4.7625 cm (1.875 inch) was obtained in this study, as shown in Fig. 1. Strain and/or temperature applied to the long period grating will cause a linear shift in the grating resonance wavelength.

The long period fiber grating has to be compensated so that the optical devices have the wavelength stability for practical applications. Depending on the design of optical properties in the fiber [7], an applied strain will cause a negative shift in the resonance wavelength of the grating for a FLEXCOR fiber, while the temperature coefficient is positive. If the long period fiber grating is mounted under tension in such a way that the strain is gradually relieved as the temperature falls below the room temperature, the reducing strain compensates the reducing refractive index of the grating. If temperature rises, the increasing strain compensates the increasing refractive index, and can hold the resonant wavelength constant.

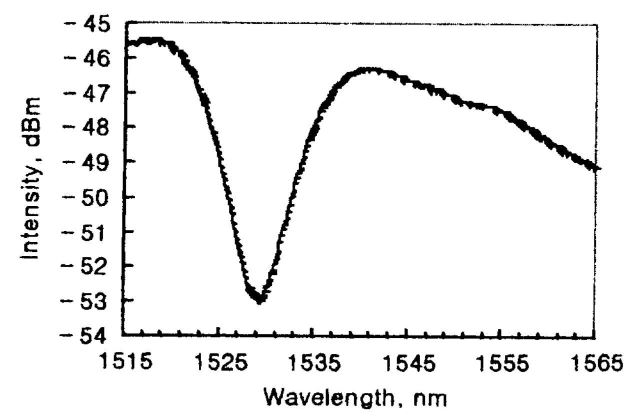

FIG. 1. The Typical Transmitted Spectrum of the Long Period Grating.

II. B. Design of a Temperature-Compensating Package

The schematic view of the temperature-compensating package designed in this work is depicted in Fig. 2 used for the long period fiber grating. L_I is the total length of a package and L_G is the length of a grating, as shown in Fig. 2. The length of brass, L_B, will be

$$L_B = L_I - L_G. \tag{2}$$

For a change in temperature, invar, brass and a fiber grating will expand according to their thermal expansion coefficients, α_i, α_b, and α_g, respectively. The grating in the fiber will expand to compensate the peak wavelength in the fiber grating with changes in temperature. An effective thermal expansion coefficient, α_g, is the term used to describe the thermal expansion of the grating which can be determined by measuring the strain dependence and the temperature dependence. The effective thermal expansion coefficient of the grating means the slope of strain to temperature to maintain the grating wavelength constant with varying temperature. The sensitivity to temperature for a strain of a grating, α_g, can be easily obtained by applying the chain rule of derivatives of the strain dependence and the temperature dependence. It is noted that the effective thermal expansion coefficient of the fiber grating includes the temperature dependence of the refractive index of the grating. Considering the rule for conservation of change in length with an increase in heat, ΔT, the Eq. (2) can be obtained directly

$$\Delta L_I = \Delta L_B + \Delta L_G, \ (\Delta L_I = L_I \alpha_i \Delta T, \\ \Delta L_B = L_B \alpha_b \Delta T, \ \Delta L_G = L_G \alpha_g \Delta T). \tag{3}$$

We can then derive the equation for temperature-compensation given by

$$L_I = L_G \frac{\alpha_g - \alpha_b}{\alpha_i - \alpha_b}. \tag{4}$$

According to the above equation, if one knows the length between the glued joints of the grating, L_G, one can then calculate the length of a package required to compensat the temperature dependence of the grating wavelength. A temperature compensation package for

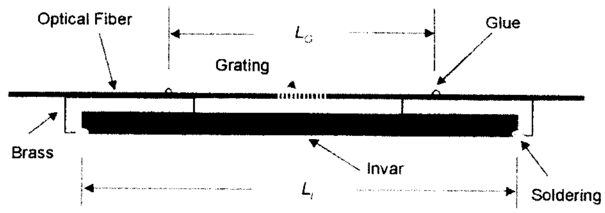

FIG. 2. The Schematic View of the Temperature-Compensating Package.

a fiber Bragg grating can also be designed using the above equation similarly with that of a long period fiber grating.

III. EXPERIMENTS FOR TEMPERATURE-COMPENSATION

Silica and invar are suitable for the component of the package with a low thermal expansion, whereas aluminum, stainless steel, brass, nylon, and teflon are suitable for the component for the package with a high expansion. The values of the thermal coefficients for the materials to be used in a passive temperature-compensating package are given in the Table 1.

III. A. Experimental Apparatus

Schematic experimental setup for measuring the strain vs. the shift in the grating wavelength and mounting the fiber on the package is illustrated in Fig. 3. The optical spectrum analyzer monitors the resonance wavelength of the grating when the bare fiber is stretched with a micrometer attached to the fiber holder. In the case of mounting the fiber on the package, the optical fiber is glued on the mount in the package once the fiber is sufficiently stretched with appropriate amount of strain within a proof-test strain, approximately 1 %.

The schematic illustration of an experimental apparatus for measuring the performance of temperature compensation of a package is shown in Fig. 4. Laser light was sent into the optical fiber on the optical package and was monitored with the optical spectrum analyzer (ANDO Model AQ-6315E) at 0.05 nm wavelength resolution to detect the grating peak wavelength as the temperature was increased.

TABLE 1. The Values of the Thermal Coefficients for the Materials to be Used in Temperature Compensation[15].

Materials	Coefficients of Thermal Expansion, /°C
Invar	0.7×10^{-6}
Stainless Steel	1.7×10^{-6}
Brass	1.9×10^{-6}
Aluminum	0.7×10^{-6}
Copper	17.3×10^{-6}
Nylon	90×10^{-6} (measured in this work)
Teflon	137.5×10^{-6} (measured in this work)

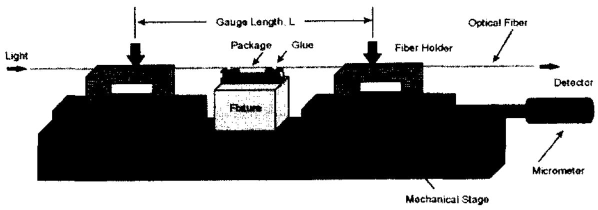

FIG. 3. Schematic View of the Translation Stage for Measuring the Strain and the Mounting of the Fiber in the Package.

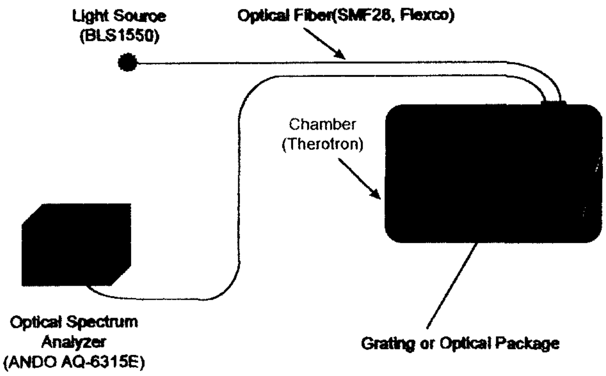

FIG. 4. Schematic View of Experimental Setup for Optical Signal Processing.

III. B. A Package for the Long Period Fiber Grating

The temperature dependence and the strain dependence of the long period fiber grating were measured, as shown in Figs. 5 and 6. The perturbations of the grating with changes in temperature and the external strain resulted in linear shifts in the resonant wavelength. The long period fiber grating exhibited large temperature coefficient of 0.048 nm/°C and the strain coefficient of -0.53 nm/mϵ on the peak wavelength, λ_g = 1528 nm, for a FLEXCOR fiber. The effect of strain on the grating is more dependent on the type of a fiber. It is noted that a FLEXCOR fiber had a negative strain coefficient. Based on measured data, the value of the effective thermal expansion coefficient of

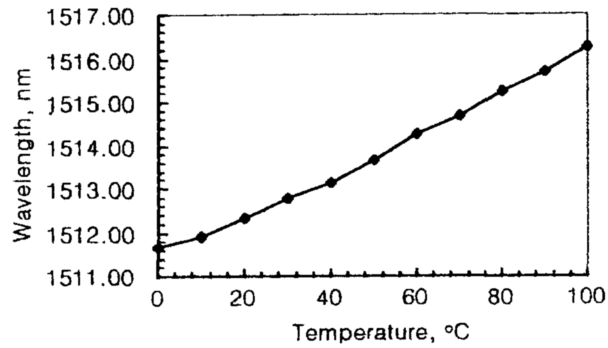

FIG. 5. The Measured Shifts in a Peak Wavelength of Long Period Grating With Temperature.

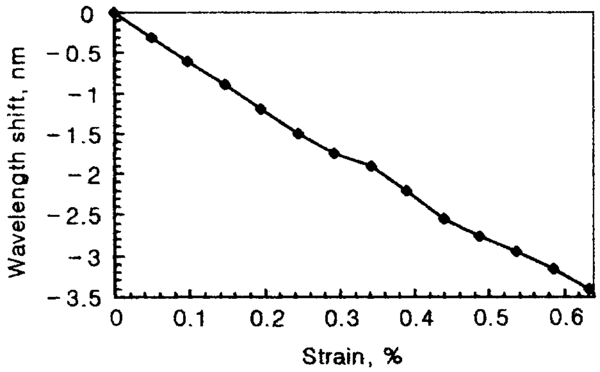

FIG. 6. The Measured Shift in the Resonance Peak Wavelength of the Long Period Grating With Strain.

TABLE 2. The Effective Expansion Coefficients of Thermal Expansion for the Bragg Grating and the Long Period Grating. (ECTE: Effective Coefficients of Thermal Expansion)

Fiber Type	Grating Type	ECTE, α_g
Ref. 3	Bragg Grating	9.2×10^{-6}
SMF28	Bragg Grating	8.5×10^{-6}
Flexcor	Long Period Grating	90×10^{-6}

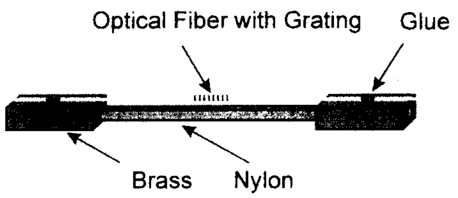

FIG. 7. The Schematic View of Temperature-Compensating Package for the Long Period Grating.

the long period fiber grating was obtained, as given in Table 2. The effective thermal expansion coefficients of the Bragg gratings were also shown to compare with that of the long period grating.

The package for the long period grating was designed with Eq. (4) by using the value of the effective thermal expansion coefficient of the optical fiber grating given in Table 2, and the coefficients of the packaging materials shown in Table 1. The package designed for a long period fiber grating in this work was schematically illustrated in Fig. 7. Brass was used as a component of low expansion, and nylon was used as the compensating member of high thermal expansion. The optical package was assembled with two pieces of brass tube, 10 mm long, and a piece of nylon rod, 45.4 mm long. The nylon rod was polished to a square shape and inserted into the brass in square tube shape, 4 mm × 4 mm, and pinned with the square brass tube. In the case of a FLEXCOR fiber, the pinned joints coincide with the epoxy glued points of the fiber because the effective thermal expansion coefficient of the grating is the same as that of nylon. (Refer to Tables 1 and 2). This means that only nylon works as the temperature-compensating component for this fiber grating. If the fiber grating has a different effective thermal expansion coefficient from that of the nylon, the brass must expand as the compensation component with the nylon. To assemble the optical fiber on the package, the optical fiber was clamped and stretched on the translation stage until the transmission peak wavelength shifted approximately by 2.4 nm ~ 3.2 nm corresponding to 0.45 % ~ 0.6 % strain. The fiber might be broken once the fiber grating is stretched to over 3.2 nm shift in the peak wavelength because the limitation on the strain emerged as 0.6 % ~ 0.82 % for a grating of the bared Flexcor fiber in this study. The fiber mounted on the brass tube of a package was glued with epoxy (AE 10) 10 mg, mixed with a hardener 1.5 mg and silica powder 1.5 mg. The transmission spectrum of the grating was monitored with the optical spectrum analyzer during the process of mounting. The distance between the mounting points was the same length as that of the grating, 25.4 mm long. The epoxy glue was cured for 24 hours, and additionally heated at 100 °C for 1 hour in order to have a thermal strength at high temperature. It is important to note that the fiber shrank back due to the spring back of the cured epoxy when the clamping force was removed to release the fiber. The grating peak wavelength shift due to the spring back of the cured epoxy was 0.4 nm ~ 0.5 nm corresponding to 0.075 % ~ 0.094 % strain of the fiber.

Laser light was sent into the optical fiber on the optical package and was monitored with the optical spectrum analyzer to detect the temperature-induced shifts in the grating peak wavelength. The temperature was held constant for 15 minutes so that the temperature of the package became an isothermal steady state in heat conduction into the package at every increase in temperature. When the grating peak wavelength did not shift and remained stable at a given temperature, the optical signal was recorded. In the case of increasing temperature, the nylon rod component expanded so that the distance between the points increased. Due to higher coefficient of the nylon than that of the brass, the packaged device always expanded to cancel the shift in the grating peak wavelength with increases in temperature. Inversely, in the case of a decrease in temperature, the nylon rod component shrank more than a brass so that the distance between the points decreased. Thus, the package compensated the temperature dependence of the fiber grating by varying the strain in the grating in proportion to and opposite to the temperature change.

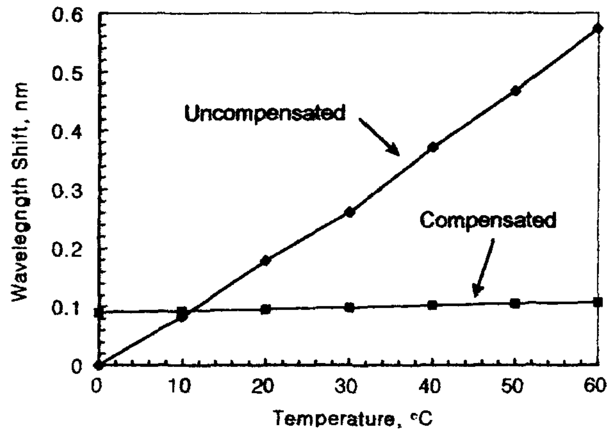

FIG. 8. Variation of the Bragg Wavelength With Temperature Change for a Compensated and an Uncompensated Bragg Grating.

IV. RESULTS AND DISCUSSION

IV. A. The Fiber Bragg Grating

The compensation for the Bragg grating was also performed to experimentally identify the design rule of the packaging because the packaging of the fiber Bragg grating is relatively more easily fabricated than that of the long period and is still interesting for optical applications in practice. Fig. 8. shows the measured shifts in the Bragg wavelength for a compensated grating and for an uncompensated grating with changes in temperature. These results show the grating was a little under-compensated. The total variation of the grating wavelength over the range of temperature from 0 °C to 60 °C was 0.018 nm range for the compensated grating. Thus the package reduced the sensitivity of the fiber grating to within a 0.3 pm/°C range, which is the sensitivity 0.03 times that of an uncompensated grating. It should be possible to imporve the total variation of the Bragg wavelength with more accurate mounting of the fiber and accuracy in estimation of the grating coefficients.

IV. B. The Long Period Fiber Grating

The nylon used as the compensation member in the package could be bent with the moment loaded at the glued joints caused by high temperature-induced strain in the nylon. It is noted that the nylon should have sufficient thickness to avoid bending of the package during the process of temperature compensation at the elevated temperature. In the case of a decreasing temperature from room temperature to low temperature, the nylon would shrink significantly more than the brass, and then the fiber grating would be bent. The bending of a grating will cause the resonant grating peak to disappear during the temperature-compensating process at low temperature without sufficient pre-strain of the fiber when the strain is pre-applied to the fiber during mounting. However, there is a limitation of fiber stretching. The pre-applied strain to the long period grating might result in the breakage of the optical fiber due to a decrease in strength of the fiber caused by UV exposure, as mentioned in the previous section. These factors limit the performance of the package and the workability in fabrication of a passive compensating package. It is suggested that the strength of the UV exposed fiber be improved for a long-term reliability and workability.

Fig. 9 shows results of the performance of the package for the long period grating, comparing with that of the uncompensated grating. The maximum variation in the resonance peak wavelength of a compensated grating over the range from -3 °C to 70 °C is 0.16 times that of an uncompensated grating. The total variation in the resonance peak wavelength of the compensated grating was 0.5 nm range over the range of operating temperatures with which the package held shifts in the grating wavelength to a 6.8 pm/°C range. The package fabricated in this work was limited to only the 73 °C range of operating temperatures 73 °C because the reduced strength of the fiber exposed to ultraviolet limited the performance of the package and the workability. A fiber grating of enhanced strength would be desired to be used in the package in order to perform the compensation over a wide range of operating temperatures. Upon investigation of the strength of fiber Bragg gratings in the literature [16,17], pulsed UV exposure of the optical fiber, as well as the fiber aging and corrosion effects, appeared to accelerate the growth of surface defects introduced during the process of removing the polymer jacket [16]. Furthermore, it is of interest to note that the decrease in the tensile

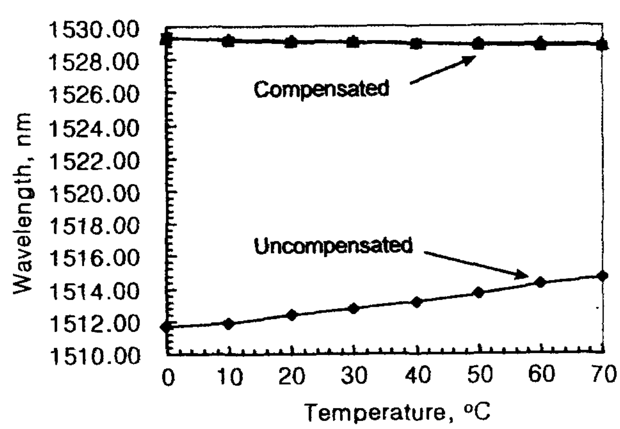

FIG. 9. Variation of the Resonance Peak Wavelength With Temperature Change for a Compensated and an Uncompensated Long Period Grating.

strength of the fiber is attributed to stress induced in the fiber surface by the ultraviolet exposure, and is dependent upon the ultraviolet wavelength [17]. It was suggested in the literature, therefore, that fabrication of the fiber grating by exposure of the ultraviolet at lower wavelength is preferable [17], and that in the future the gratings are annealed at appropriate temperature to remove unstable UV-induced defects [18].

This result of compensation seems to be acceptable in practical applications, although this presents a little bit overcompensated outcome caused by inaccurate estimation in coefficients of the materials used in the package and inaccuracy in the epoxy-glued positioning.

V. SUMMARY

We demonstrated that the temperature-induced variation of the resonant wavelength of a fiber grating can be compensated by varying the pre-applied strain of the long period fiber gratings, using a passive, compact, and rugged mount consisting of two materials, nylon and brass, with different thermal expansion coefficients. We showed that devices can compensate the temperature-induced wavelength shifts of the grating by an order of magnitude for the long period fiber gratings. These packages can be used for applications in optical devices such as gain equalizers, WDMs, add/drop couplers, and external laser mirrors, etc. acquiring wavelength stability with changes in temperature. The reduced strength of the fiber by exposure of ultraviolet limits the performance of this package to over the range of operating temperatures from -3 °C to 70 °C. Strength improvement of the fiber exposed by ultraviolet is desired so as to obtain the performance of the package at a wide range of operating temperatures and long-term reliability in practical applications.

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