Simultaneous temperature and bend sensing with long-period fiber gratings

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Long-period gratings (LPG's) written in commercially available boron-codoped fibers operating at wavelengths of <1.1 μm are shown to exhibit high temperature and bending sensitivities. Each resonant attenuation band of such LPG's was observed to split in two when the LPG's were bent. The split attenuation bands' separation increased significantly with increasing bend curvature, and the central wavelengths of the split bands provided a measure of temperature. We exploit this effect to allow for simultaneous measurement of temperature and bending in smart-structure applications. The demonstrated novel sensor system is simple and low cost.

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Long-period fiber gratings (LPG's) recently attracted much attention for use in optical sensing applications[1,2] and optical communication systems.[3] The unique characteristic of LPG's is that the wavelength shifts of the spectral attenuation bands induced by a measurand, such as temperature, strain, or bending of the fiber, depend strongly on the structure and composition of the fiber, the periodicity of the LPG, and the operating wavelength. This characteristic offers many possibilities for developing LPG sensors for a range of applications.[1,2,4,5] However, minimizing the cross talk between different measurands, especially between bending and temperature, is important for developing LPG sensors in smart-structure applications. The LPG sensors that have been developed so far for temperature and strain sensing require special rigid packaging so that bending of the fiber can be avoided, and the strong effects of temperature need to be considered for the LPG bend sensor reported in Ref. 4.

To date, most LPG's have been fabricated to operate at wavelengths $\geq$1.2 μm.[1–6] The key criteria for determining the operating wavelength of a LPG sensor are suitability, availability, and the cost of the signal sources, demodulation systems, and LPG's. As low-cost CCD spectrometers operating at wavelengths of up to 1.1 μm have become commercially available, it is practical to develop LPG sensors at shorter wavelengths. In this Letter we investigate the characteristics of LPG's operating at shorter wavelengths (<1.1 μm) for temperature, strain, and bend sensing. A novel approach for simultaneous measurement of temperature and bend curvature is demonstrated.

LPG's were fabricated with a frequency-quadrupled Nd:YAG laser operating at a wavelength of 266 nm, with a pulse width of 5 ns and a repetition rate of 10 Hz. The LPG was formed by use of a point-by-point exposure technique. The focused UV intensity was approximately 0.9 J/cm^2, and the exposure time for each point was 30 s. LPG's were written in a boron-codoped photosensitive silica fiber (Fibercore PS750), with a cutoff wavelength of 750 nm, which was not hydrogen loaded. After exposure of the LPG's, we annealed them at 180 °C for 3 h to stabilize the spectral characteristics.

For temperature-, strain-, and bend-sensing experiments, a section of fiber with the LPG in the center was held between two V grooves. One V groove was fixed, and the other was mounted on a translation stage. We investigated the temperature dependence of the LPG's by locating them within an 18-cm-long furnace with a diameter of 14 mm and a temperature resolution of 1 °C. We applied axial strain to the LPG by increasing the separation of the *V* grooves, using the translation stage. For the bend test we bent the fiber by moving the translation stage toward the fixed V groove, we estimated and the curvature of the bend by approximating the bent fiber as the arc of a circle.[4] The effects of the measurands were monitored by measurement of the transmission spectrum of the LPG over wavelengths ranging from 800 to 1100 nm by use of a fiber-coupled white-light source and a CCD spectrometer (Ocean Optics S2000). The CCD has a minimum integration time of 1 ms. The transmission spectra were transferred to a personal computer for processing. The central wavelength of each attenuation band was determined through a quadratic fit of the band by use of the average transmission spectrum. The center-to-center pixel spacing of the CCD corresponds to 0.3 nm; however, as the image of each attenuation band is spread over tens of pixels, the central wavelength of the attenuation band can be determined with much higher resolution,[7] 0.05 nm in this experiment.

Table 1 summarizes the properties of the tested LPG's. The periodicities of the LPG's ranged from 300 to 600 μm, and the grating length ranged from 36 to 46 mm. For all the LPG's, the central wavelengths of the attenuation bands shifted to shorter wavelength with increasing temperature, and the temperature responses of the central wavelengths were linear in the tested temperature range up to 150 °C. For each LPG the maximum temperature sensitivity was recorded on the attenuation band with the longest central wavelength (referred to as attenuation band I). The temperature sensitivities in the table, measured when

Table 1. Tested LPG's

Parameter	A	B	C	D
Grating period (μm)	300	400	450	600
Grating length (mm)	36	40	41	46
Temperature sensitivity (nm/°C)				
Attenuation band I	−0.191	−0.256	−0.207	−0.224
Attenuation band II	−0.151	−0.164	−0.164	−0.175
Central wavelength (nm) (at 30 °C)				
Attenuation band I	928	1058	1019	1098
Attenuation band II	862	950	946	1008

the fibers were straight, are generally higher than the previously reported temperature sensitivities of LPG's written directly in conventional fibers.[1,5] The bend-response characteristics were tested for LPG's C and D. The dimensions of the furnace and the separations of two V grooves limited the maximum bending curvatures that could be applied to LPG C and LPG D to 1 m^{-1} and 1.57 m^{-1}, respectively.

When the LPG was bent, each resonant attenuation band was observed to split in two, and the separation increased significantly with increasing bend curvature. Figure 1 shows the transmission spectra of LPG D with curvature ranging from 0 (straight) to 1.31 m^{-1}. The formation of dual peaks for a high-order cladding mode (LP_{015}) was observed and explained in Ref. 6. The possible mechanism for the band splitting in our LPG's is that the phase-matching condition for the cladding mode could be satisfied at two discrete wavelengths when the fiber was bent.

The dependence of the wavelength separation of the split attenuation bands on the curvature for attenuation band II of LPG D was measured at a temperature of 30 °C and is plotted in Fig. 2. A wavelength separation larger than 30 nm was recorded when the curvature increased to 1.5 m^{-1}. The measured bending sensitivity is 1 order of magnitude higher than that reported in Ref. 4.

We performed further experiments on LPG C to characterize the LPG's response to temperature for different bending curvatures and in different directions. When LPG C was written, the side of the fiber facing the UV beam was marked with two Scotch tape flags. When the LPG was bent in such a direction that the fiber side facing the UV beam was on the outer surface of the fiber arc, the direction was referred to as $\theta = 0°$. When the fiber was rotated by 180° and bent in the opposite direction, the direction was referred to as $\theta = 180°$.

In Fig. 3 the measured central wavelength(s) for attenuation band II are plotted versus temperature when the fiber was straight and when it was bent in opposite directions with a curvature of 0.92 m^{-1}. Figure 3 shows that the temperature responses of the central wavelengths for all bands were linear, with a temperature sensitivity of 0.164 ± 0.004 nm/°C, independent of whether the LPG was straight or bent. When the fiber was bent, the wavelength separation of the two split bands was a constant for a range of temperatures from 30 to 150 °C. The wavelength shift of a split band induced by temperature change ΔT and bending-curvature change ΔB can be written as $\Delta\lambda_i = K_T \Delta T + \Psi(\Delta B)$ $(i = 1, 2)$, where K_T is the temperature coefficient and $\Psi(\Delta B)$ is the wavelength shift induced by ΔB. Since the temperature coefficients are the same for all split bands, the wavelength separation gives a measure of the bend curvature. From a knowledge of the function $\Psi(\Delta B)$ and the wavelength shift $\Delta\lambda$, the temperature can be calculated.

At large bending curvatures, the large wavelength separation of the split bands may result in different temperature sensitivities for the two split bands. In these conditions, the bend-induced wavelength separations of the split bands are not independent of temperature. For this case a lower-order cladding mode with less sensitivity to bending can be used instead in the same way as described previously.

Although the wavelength separation does not show a linear dependence on bending curvature over the full range tested, it is informative to analyze the accuracy and stability of the system for a smaller range of bending curvature within which the dependence of wavelength shifts of the split bands on the curvature is

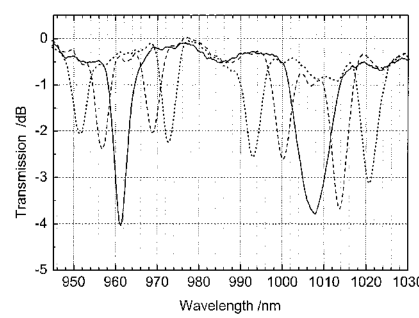

Fig. 1. Transmission spectra of LPG D for $T = 30$ °C and different bend curvatures: (———) straight, (– – – –) 0.75-m^{-1} curvature, (·········) 1.31-m^{-1} curvature.

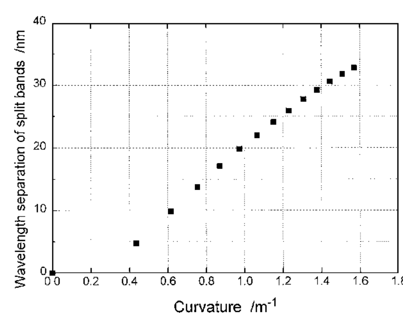

Fig. 2. Central-wavelength separation of the split attenuation bands versus bend curvature for LPG D. $T = 30$ °C.

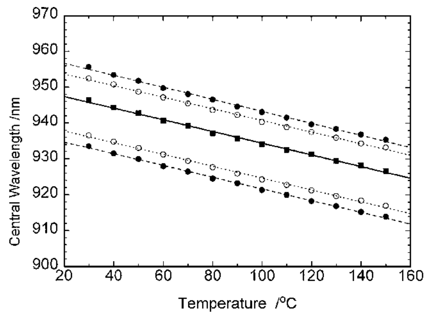

Fig. 3. Central wavelengths of the attenuation bands versus temperature when LPG C was straight and when it was bent with a curvature of $0.92\ m^{-1}$ in different bending directions: (—■—■—) straight, (···○···○···) bent, $\theta = 0°$, (●–●) bent, $\theta = 180°$.

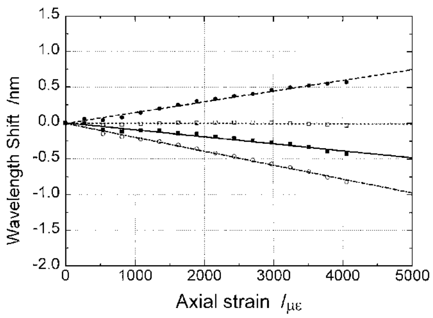

Fig. 4. Central-wavelength shift versus axial strain for LPG D. The strain sensitivities for the four bands are -1.0×10^{-4} nm/$\mu\epsilon$ (—■—■—, attenuation band II), -1.9×10^{-4} nm/$\mu\epsilon$ (○–○, 962-nm band), 1.5×10^{-4} nm/$\mu\epsilon$ (●–●, 925-nm band), and -3×10^{-6} nm/$\mu\epsilon$ (···□···□···, 861-nm band).

approximately linear. When the bending curvature applied to LPG C was 0.4–$0.8\ m^{-1}$, the wavelength shifts of the two split bands of attenuation band II could be written as

$$\begin{pmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \end{pmatrix} = \begin{bmatrix} K_T & K_{B1} \\ K_T & K_{B2} \end{bmatrix} \begin{pmatrix} \Delta T \\ \Delta B \end{pmatrix},$$

where $K_{B1,2}$ are the bending coefficients of the two split bands, with $K_T = -0.164 \pm 0.004$ nm/°C, $K_{B1} = 11.2 \pm 0.3\ nm/m^{-1}$, and $K_{B2} = -14.0 \pm 0.3\ nm/m^{-1}$. This matrix is well conditioned, resulting from the fact that the two bending coefficients are of different signs. Since the bending curvature is determined independently by the wavelength separation of the split bands, the sensitivity of the system to measurement inaccuracies is very low.

It has been reported[4] that the asymmetric bend response of the fiber is due to the UV-induced noncircular symmetric changes in the fiber. Figure 3 shows that, for the same bending curvature of $0.92\ m^{-1}$, the wavelength separation induced by bending in the $\theta = 180°$ direction was 21.7 ± 0.2 nm, which was much larger than that in the $\theta = 0°$ direction, 16.1 ± 0.2 nm. Using this asymmetry of the bend-induced wavelength separation of the split bands, we could determine the direction of bending with a combination of two or three LPG's.

The response of the axial strain of the LPG's was relatively weak. Figure 4 shows the central wavelength shifts for the four different attentional bands of LPG D when strain was applied to the LPG at a temperature of 30 °C. The strain sensitivities for different attenuation bands, which ranged from -1.9×10^{-4} to 1.5×10^{-4} nm/$\mu\epsilon$, are smaller than that of a conventional Bragg grating ($\geq 6 \times 10^{-4}$ nm/$\mu\epsilon$). The temperature dependence of the strain sensitivity was also tested for temperatures up to 160 °C. For attenuation band II the strain sensitivity was -1.0×10^{-4} nm/$\mu\epsilon$ at a temperature of 30 °C, and -0.3×10^{-4} nm/$\mu\epsilon$ at 160 °C. The maximum errors for temperature and bend curvature induced by neglect of the effects of axial strain of up to 1000 $\mu\epsilon$ would be 0.6 °C and $5 \times 10^{-3}\ m^{-1}$, respectively. When a higher accuracy is required or higher axial strain is involved, a technique using measured data from two attenuation bands can be applied.[2]

LPG's written in boron-codoped fibers operating at wavelengths of approximately 1 μm are shown to exhibit much higher temperature and bending sensitivities than those of LPG's operating at a longer wavelength. Each resonant attenuation band of such LPG's was observed to split in two when the LPG's were bent. A wavelength separation larger than 30 nm was recorded when the curvature was $1.5\ m^{-1}$. For the same attenuation band the measured temperature sensitivity was -0.175 nm/°C. Since the wavelength separation of the split bands gives a measure of the bend curvature independently of temperature, measurements of the wavelengths of the split bands allows simultaneous sensing of temperature and bend curvature. Based on our demonstration of this novel effect, development of high-sensitivity, low-cost fiber sensors for structural bend and temperature sensing is promising. The response of the LPG's to axial strain was relatively small and can be neglected in practice. The asymmetric bend response of the band splitting allows determination of the bend direction.

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References

1. V. Bhatia and A. M. Vengsarkar, Opt. Lett. **21,** 692 (1996).
2. V. Bhatia, D. Campbell, R. O. Claus, and A. M. Vengsarkar, Opt. Lett. **22,** 648 (1997).
3. A. M. Vengsarkar, P. J. Lemaire, J. B. Judkins, V. Bhatia, T. Erdogan, and J. E. Sipe, J. Lightwave Technol. **14,** 58 (1999).
4. H. J. Patrick, C. C. Chang, and S. T. Vohra, Electron. Lett. **34,** 1773 (1998).
5. Y. G. Han, C. S. Kim, K. Oh, U. C. Paek, and Y. Chung, Proc. SPIE **3746,** 58 (1999).
6. X. Shu, X. Zhu, Q. Wang, S. Jiang, W. Shi, Z. Huang, and D. Huang, Electron. Lett. **35,** 649 (1999).
7. E. J. Friebele, C. G. Askins, A. B. Bosse, A. D. Kersey, H. J. Patrick, W. R. Pogue, M. A. Putnam, W. R. Simon, F. A. Tasker, W. S. Vincent, and S. T. Vohra, Smart Mater. Struct. **8,** 813 (1999).