Simultaneous measurement of axial strain, temperature, and transverse load by a superstructure fiber grating

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A novel and simple fiber-optic sensor based on a superstructure fiber grating for simultaneous measurement of temperature, axial strain, and transverse load is proposed and demonstrated. By measurement of the shift and split of broadband and narrow-band loss peaks, one can determine the temperature, axial strain, and transverse load simultaneously over the ranges 0–140°, 0–1200 $\mu\epsilon$, and 0–0.3 kg/mm, respectively. © 2001 Optical Society of America

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Considerable research effort has been devoted to the development of fiber Bragg grating– (FBG-) based sensors for measurement of temperature, strain, and other physical parameters. Many effective methods based on FBGs have been developed to measure strain and temperature simultaneously.[1,2] Recently, long-period gratings (LPGs) have been demonstrated as individual sensors for temperature, strain, and transverse-load measurement, with higher sensitivities than those of FBGs.[3,4] The superstructure fiber grating (SFG) is a special type of FBG that uses periodically modulated exposure over the length of a phase mask.[5] Similarly to a FBG, the SFG couples the forward-propagating LP_{01} mode to the reverse-propagating LP_{01} mode at a series of narrow-band loss peaks in the transmission spectrum (as shown in Fig. 1). The SFG also functions as a LPG that couples the forward-propagating LP_{01} mode to the forward-propagating cladding modes and introduces broadband loss peaks in the transmission spectrum. For multiparameter measurement, SFG has been used successfully to determine temperature and axial strain simultaneously.[6] In this Letter, we demonstrate a novel application of SFG to measurement of temperature, axial strain, and transverse load simultaneously.

The wavelengths of the broadband and the narrow-band loss peaks are sensitive to temperature and axial strain, with different sensitivities.[3] In addition, the broadband peak will split as a result of birefringence induced under a transverse load.[4] In our experiment, we select one broadband and one narrow-band loss peak to demonstrate the sensing principle. Figure 2 shows the original and the changed spectra of a SFG subject to simultaneous variation in temperature, strain, and load, where only one narrow-band loss peak is shown and the wavelength shift and the mode split are exaggerated. In previous work, it was shown that the peak wavelengths of LPGs and FBGs change linearly with temperature and axial strain, and the mode split of the LPG loss peak and the transverse load also have a linear relation.[3,4] Our experiment confirms these linear relationships. In Fig. 2, λ_{Bo} and λ_{No} are the original wavelengths of the broadband and the narrow-band loss peak, respectively; λ_{B} and λ_{N} are the wavelengths shifted as a result of temperature and strain change; λ_{Bx} and λ_{By} are the wavelengths of the broadband x- and y-polarizing modes as a result of transverse-load-induced birefringence. The relationship among temperature T, axial strain ϵ, and transverse load L can be expressed as

$$\lambda_N = AT + B\epsilon + \lambda_{No}, \tag{1}$$

$$\lambda_B = CT + D\epsilon + \lambda_{Bo}, \tag{2}$$

$$\lambda_{Bx} = \lambda_B + EL, \tag{3}$$

$$\lambda_{By} = \lambda_B + FL, \tag{4}$$

where A–F are coefficients. By redefining the variants as $\Delta\lambda_1 = \lambda_N - \lambda_{No}$, $\Delta\lambda_2 = \lambda_{Bx} - \lambda_{Bo}$, and $\Delta\lambda_3 = \lambda_{Bx} - \lambda_{By}$, we can obtain

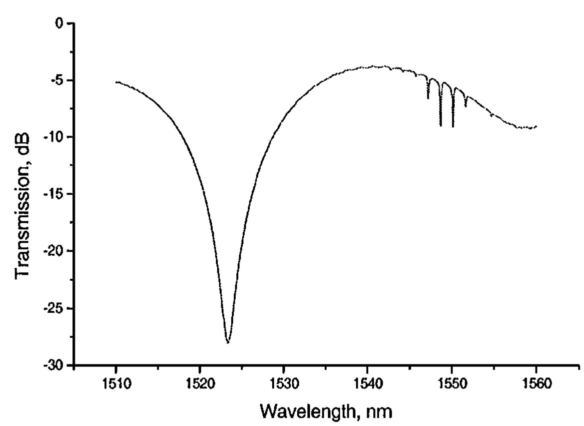

Fig. 1. Transmission spectrum of a SFG.

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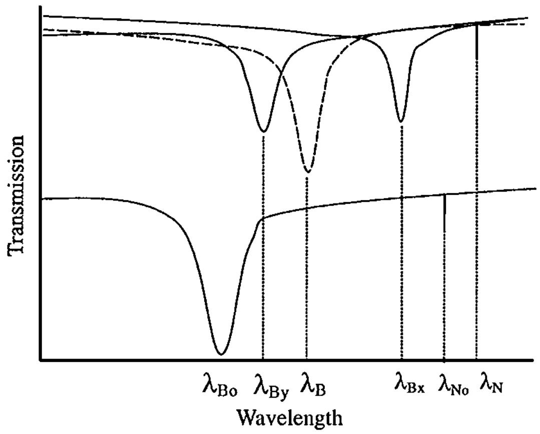

Fig. 2. Change of superstructure fiber grating spectrum under external perturbation. Bottom curve, original spectrum. Top curves, spectrum under temperature, strain, and load (dashed curve, spectrum under free load; solid curves, x- and y-polarizing mode spectra, respectively, under transverse load.

$$\Delta\lambda_1 = AT + B\epsilon\,, \tag{5}$$

$$\Delta\lambda_2 = CT + D\epsilon + EL\,, \tag{6}$$

$$\Delta\lambda_3 = (E - F)L = F'L\,. \tag{7}$$

In Eqs. (5)–(7), coefficients A–E and F' are determined by experiments. Equations (5)–(7) can then be expressed as

$$\begin{pmatrix}\Delta\lambda_1\\ \Delta\lambda_2\\ \Delta\lambda_3\end{pmatrix} = \begin{bmatrix} A & B & 0\\ C & D & E\\ 0 & 0 & F\end{bmatrix}\begin{pmatrix}T\\ \epsilon\\ L\end{pmatrix} = [K]\begin{pmatrix}T\\ \epsilon\\ L\end{pmatrix}\cdot \tag{8}$$

The SFG was inscribed in a hydrogen-loaded Corning 28 single-mode fiber (after decoating) by use of a 10-mm uniform phase mask, a 30-mm amplitude mask with a period of 550 μm, and a 193-nm ArF excimer laser with exposure conditions of 150 mJ/cm^2 per pulse at 10 Hz for 4 min. The hydrogen-load condition was 140 atm for 7 days. During the writing process, the amplitude mask was placed on top of the phase mask. Then we annealed the SFG in an oven at 140 °C for 12 h to remove any unreacted hydrogen and unstable UV-induced defects.

The experimental setup for determining the temperature, axial strain, and transverse-load coefficients is shown in Fig. 3. The SFG was placed in an environmental chamber with temperature control. We measured temperature coefficients A and C by heating the SFG, free of any axial strain or transverse load. Figure 4a shows the wavelength shift of the narrow-band loss peak and the broadband loss peak with respect to temperature. The sensitivities of the peaks were measured as 0.01 and 0.04 nm/°C, respectively, over the range 20–140 °C. To measure the axial strain coefficients, we applied an axial strain to the SFG by fixing both ends of the grating and stretching the SFG by use of a translation stage. The SFG was maintained at 20 °C within a temperature controller and no transverse load. The wavelengths of the narrow-band and broadband loss peaks vary linearly with strain over the range 0–1200 $\mu\epsilon$. The values of B and D were derived as 8.04×10^{-4} and 1.98×10^{-3} nm/$\mu\epsilon$, respectively. Figure 4b shows the wavelength shifts of the narrow-band and the broadband loss peaks with respect to axial strain. Transverse-load coefficients E and F were determined under free axial strain at 20 °C. Compared with that of the broadband loss peak, the mode split of the narrow-band loss peak is rather small, less than 0.2 nm at the maximum load of 0.3 kg/mm. Hence, its effect on the measurement results can be neglected. The values of E and F were estimated, by use of linear regression, as 57.73 and 71.76 nm/(kg/mm), respectively. Figure 4c shows the response of $LP_{04}{}^{x}$-mode wavelength shift and the mode split of the broadband loss peak (the wavelength difference between the

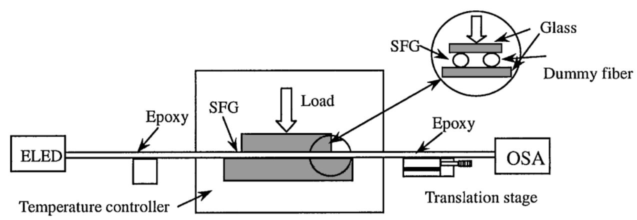

Fig. 3. Experimental setup for determining the temperature, strain, and transverse load coefficients of a SFG. ELED, edge light-emitting diode; OSA, optical spectrum analyzer.

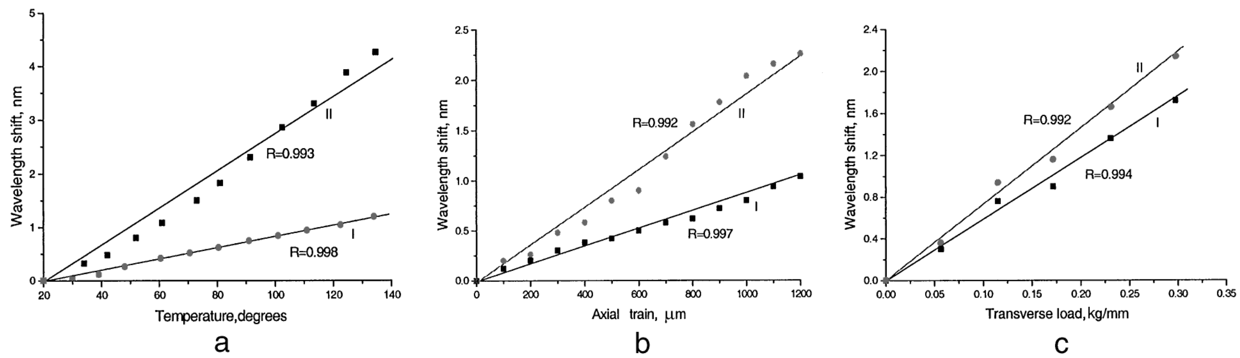

Fig. 4. Response of superstructure fiber grating under external perturbation: a, Temperature response: I, narrow-band loss peak ($R = 0.998$); II, broadband loss peak ($R = 0.993$). b, Axial strain response: I, narrow-band loss peak ($R = 0.997$); II, broadband loss peak ($R = 0.992$). c, Transverse-load response: I, $LP_{04}{}^{x}$ mode shift ($R = 0.994$); II, mode split $\lambda(LP_{04}{}^{x}) - \lambda(LP_{04}{}^{y})$ ($R = 0.993$).

$LP_{04}{}^{x}$ and $LP_{04}{}^{y}$ modes) with respect to the transverse load.

Hence the matrix $[K]$ and its inverse matrix are

$$[K] = \begin{bmatrix} A & B & 0 \\ C & D & E \\ 0 & 0 & F' \end{bmatrix} = \begin{bmatrix} 0.0110 & 8.044 \times 10^{-4} & 0 \\ 3.998 \times 10^{-2} & 1.98 \times 10^{-3} & 57.718 \\ 0 & 0 & 71.756 \end{bmatrix}, \tag{9}$$

$$[K]^{-1} = \begin{bmatrix} -192.24 & 78.10 & -62.82 \\ 3872.04 & -1068.02 & 859.07 \\ 0 & 0 & 0.0139 \end{bmatrix}. \tag{10}$$

In this Letter, we have demonstrated simultaneous measurement of temperature, axial strain, and transverse load by use of a SFG. The proposed fiber grating sensor has the advantage of simple and easy fabrication of single-step UV exposure by use of an amplitude mask with a phase mask. In addition, only one broadband sources is required for the sensor. Since SFGs integrate the properties of LPGs and FBGs in a short length, the proposed sensor offers the prospect of further development of multiaxis measurement, with the possibility of simultaneous temperature measurement. As the response of LPGs of external perturbation are highly dependent on fiber type, selected cladding mode, and recoating conditions,[3,7] and therefore the response coefficients can be optimized for further improvement in performance. This is under study by the present authors.

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