New Method to Obtain Strain Gradient Chirped Fiber Bragg Gratings *

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We describe a new method for applying a strain gradient with different profiles to convert uniform fiber Bragg gratings into linear or non-linear chirped ones. The chirping profile and the chirp rate of the fiber gratings can be controlled by simply varying the tension applied. Both the theory and experimental results are presented.

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Since the maturity of fiber amplifier technology, chromatic dispersion has become the dominantly limiting factor to the capacity of optical fiber communication. At the same time, the study of the photosensitivity of the fiber[1−3] makes it possible to fabricate fiber gratings in fibers. Now chirped fiber grating is considered one of the best devices to compensate the chromatic dispersion of fiber. The idea that chirped fiber Bragg gratings can be used for dispersion compensation was first proposed by Francois Ouellette in 1987,[4] which led to the development of techniques for fabricating chirped fiber gratings in the last few years.[5−7] As periodic phase masks are the most popular and are used in fabrication of fiber gratings, various techniques have been developed for chirping periodic fiber gratings, in some of which epoxy induced strain gradient,[8] temperature gradient[9] and non-uniform magnetic fields[10] were used. These techniques allow the center wavelength and spectral width to be well controlled after the uniform fiber grating has been fabricated. In this article we describe a new method of introducing a strain gradient with different profiles for chirping the fiber gratings, including the theoretical analysis and some experimental results.

The Bragg wavelength at an axial position z of a fiber grating is given by

$$\lambda_B(z) = 2\overline{n(z)}\Lambda(z), \tag{1}$$

where $\overline{n(z)}$ is the mean refractive index (averaged over the grating period) at position z and $\Lambda(z)$ is the grating period at position z. Thus chirped gratings can be achieved by axially varying either $\overline{n(z)}$ or $\Lambda(z)$ (or both). As we know, if tension is applied to both ends of a fiber grating the induced strain is uniform throughout the grating, resulting in a uniform Bragg wavelength shift but no change in the shape of the reflection spectrum of the grating. This means that $\Lambda(z)$ is still constant throughout the grating and the grating is not chirped. In other words, to produce a non-uniform distribution of $\Lambda(z)$, a strain gradient is required.

In Ref. 8, a stress gradient in a fiber is induced by the surrounding adhesive and so could be hard to control. We propose to introduce a strain gradient directly in a fiber grating by gluing the fiber onto the substrate, such as an aluminum sheet, with its cross section specially designed. When we apply tension to both ends of such an aluminum sheet, the resulting strain is determined by

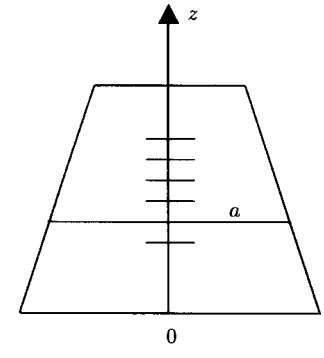

Fig. 1. Aluminum sheet with fiber grating glued on it.

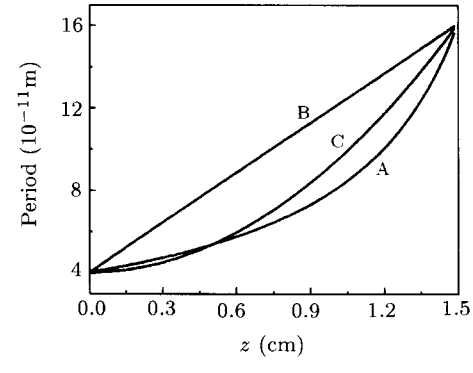

Fig. 2. Variation of the grating period versus axial position z for different aluminum sheet shapes A, B, and C.

$$\Delta L(z) = \frac{F}{ES(z)}\delta L, \tag{2}$$

where F is the applied tension, $E = 6.0 \times 10^6\,\mathrm{N/cm^2}$ is the Young's modulus of aluminum, $S(z)$ is the area of the cross section at position z and δL is an arbitrary length at position z. If a fiber grating is firmly

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glued on such an aluminum sheet, it will suffers from the same strain as in the aluminum sheet. Then the variation of the grating's period along the axis can be expressed as

$$\Delta\Lambda(z) = \frac{F}{ES(z)}\Lambda_0, \tag{3}$$

where Λ_0 is the period of the grating. As $\Lambda(z) = \Lambda_0 + \Delta\Lambda(z)$ varies along the axial direction, the chirping of the fiber grating depends on the shape of $S(z)$.

Now, the elasto-optic effect must be further taken into account.[11] The strain inside the fiber will cause an index change and, in turn, change the Bragg wavelength and the reflection spectrum of the fiber grating. After we take this effect into account, we get

$$\lambda_B(z) = 2[\overline{n_0(z)} + \Delta n(z)] \cdot [\Lambda_0(z) + \Delta\Lambda(z)], \tag{4}$$

where $\Delta n(z)$ is caused by the elasto-optic effect. Since $\Delta n(z) \cdot \Delta\Lambda(z)$ can be neglected, from the above expressions we obtain

$$\Delta n(z) \cdot \Lambda_0(z) = -0.22\overline{n_0(z)} \cdot \Delta\Lambda(z). \tag{5}$$

In order to analyze the characteristics of the chirped fiber grating, we adopt the fundamental matrix approach described in Ref. 12 and divide the chirped grating into N segments. Each segment is dealt with as a short periodic grating, which is described by a matrix F^k $(k = 1, 2, \cdots, N)$. The elements of the F^k matrix are given as follows:

$$F_{11}^k = [\cosh(\gamma L) + \frac{\mathrm{i}}{\gamma L}\Delta\beta L\sinh(\gamma L)]\exp(\mathrm{i}\beta_B L)$$

$$F_{12}^k = -\kappa L\sinh(\gamma L)\frac{1}{\gamma L}\exp[-\mathrm{i}(\beta_B L + \phi)]$$

$$F_{21}^k = -\kappa L\sinh(\gamma L)\frac{1}{\gamma L}\exp[\mathrm{i}(\beta_B L + \phi)]$$

$$F_{22}^k = [\cosh(\gamma L) - \frac{\mathrm{i}}{\gamma L}\Delta\beta L\sinh(\gamma L)]\exp(-\mathrm{i}\beta_B L), \tag{6}$$

where β is the propagation constant along the fiber axis, $\beta_B = \pi/\Lambda$ the grating frequency, $\Delta\beta = \beta - \beta_B$, $\gamma = \sqrt{\kappa^2 - \Delta\beta^2}$, Λ the fiber grating period, κ the coupling coefficient, L the length of the kth segment and ϕ the grating phase which satisfies the phase condition $\phi^k = \phi^{k-1} + 2\beta_B L^{k-1}$.

By multiplying the F^k matrixes, we get a matrix F describing the whole chirped grating

$$F = \prod_{k=1}^{N} F^k. \tag{7}$$

The coefficients of reflection R and transmission T are given by the F-matrix representation as follows:

$$T = \frac{1}{F_{11}}, \quad R = \frac{F_{21}}{F_{11}}. \tag{8}$$

By using this method, we calculate the reflection spectra and phase characteristics of three fiber gratings glued on aluminum sheets with different $S(z)$ shapes. Then we can obtain the reflection and phase characteristics of the fiber gratings from

$$r = |R|, \quad \varphi = \arg(R). \tag{9}$$

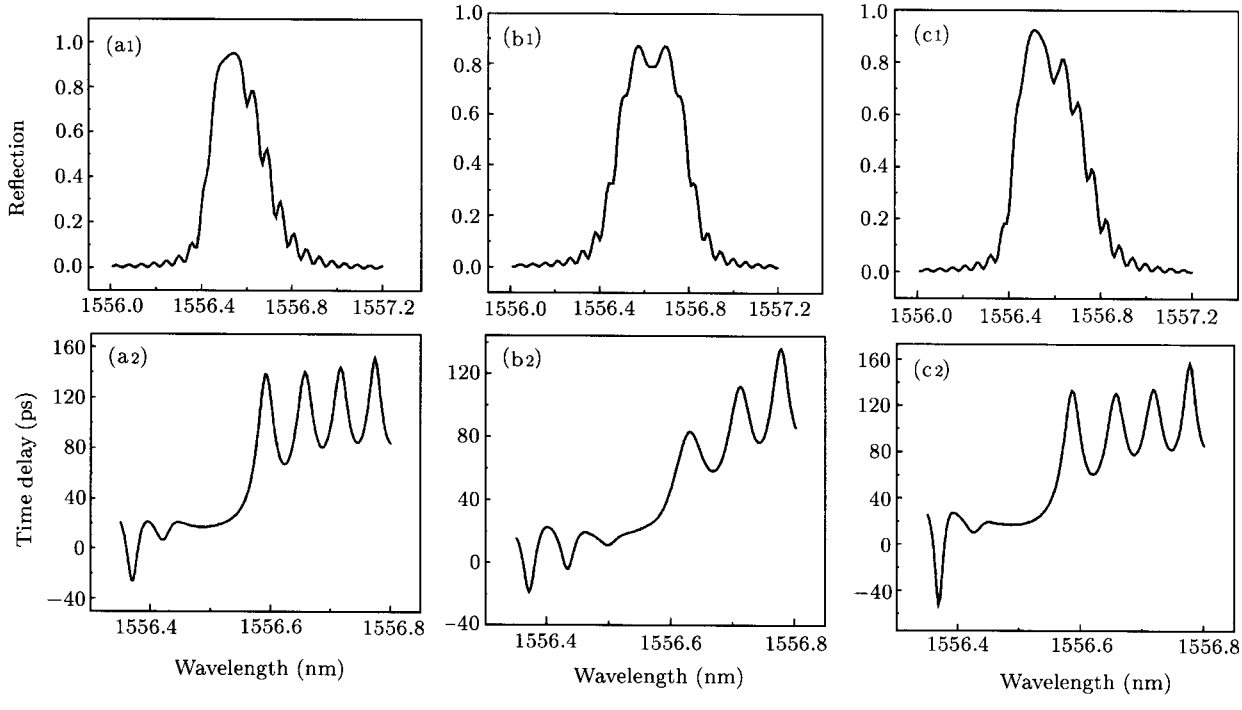

Fig. 3. Theoretical reflectivity and time delay versus wavelength for a periodic fiber grating glued on aluminum sheet of (a) shape A, (b) shape B, (c) shape C; (1) is Reflectivity spectrum, (2) time delay curve.

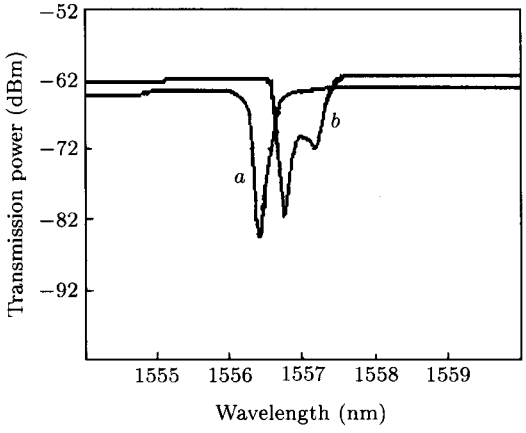

Fig. 4. Transmission spectrum of chirped fiber grating. curve *a*: Tension $F = 0$, spectral width is 0.45 nm; curve *b*: Tension $F = 17$ N, spectral width is 0.76 nm.

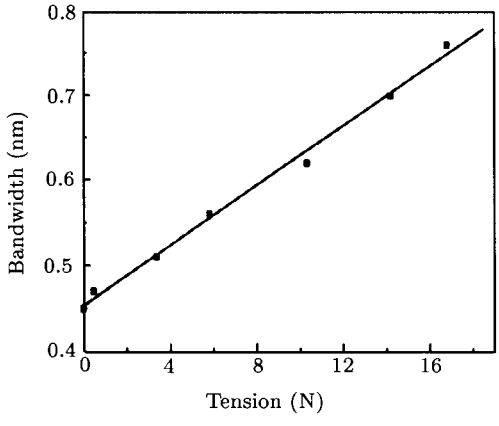

Fig. 5. Spectral width of chirped fiber grating versus applied tension.

The aluminum sheet shown in Fig. 1 has upper and lower sides of lengths 0.4 and 1.6 cm, respectively, and is 1.5 cm in height and 0.012 cm in thickness. The shape of the aluminum sheet depends only on the width $a(z)$ (as shown in Fig. 1), as the thickness is uniform in our examples. We consider three kinds of shape:

$$\text{A: } a(z) = 1.6 - 0.8z;$$
$$\text{B: } a(z) = 0.8/(0.5 + z);$$
$$\text{C: } a(z) = 1.2/(0.75 + z^2).$$

Figure 2 shows the theoretical variations of the gratings' period $\Delta\Lambda(z)$ along the fiber axis when a tension of 12 N is applied to the ends of the aluminum sheet.

Figure 3 shows the theoretical reflection and time delay of the fiber gratings stuck on different aluminum sheets when a tension of 12 N is applied, where the time delay

$$\tau = \frac{\mathrm{d}\varphi}{\mathrm{d}\omega}.$$

We use a trapezoidal aluminum sheet with shape A. A 1.5 cm long piece of uniform fiber grating is glued along its axis of symmetry. Figure 4 shows the experimental results when tensions of 0 and 17 N are applied on both ends of the sheet along the z direction.

Figure 5 shows the relationship between the spectral width of the grating and the applied tension. We can see that the spectral width is proportional to the tension, which means that the experimental setup is well controlled.

Interesting phenomena can be observed from our experiment and the theoretical analysis. First, in Fig. 5, the spectral bandwidth of the fiber grating sample is almost linearly proportional to the tension applied, which shows that the experimental setup is well controlled and that this method of chirping the fiber grating gives good stability. From Fig. 3, we observe that the time delay is affected by the chirping profile. For the case of linear chirping, which is most popular currently, the time delay varies with wavelength in the reflection band. But for the case of non-linear chirping, either with shape A or shape C, the time delay is a constant, which might be highly desirable for some applications.

The tension applied to the aluminum sheet can be as high as 17 N in the experiments, but large tensions may strain the sheet beyond its elastic limit and cause permanent deformation. This can be observed in the strain remaining in the grating after removing the applied tension.

We have demonstrated a new method to chirp fiber Bragg gratings by a strain gradient. The center wavelength and spectral bandwidth can be controlled by varying the applied tension. The time delay could be kept constant by non-linear chirping. By changing the shape of the aluminum sheet, we can chirp the fiber grating with complex profiles.

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