Variable-spectral-response optical waveguide Bragg grating filters for optical signal processing

K. O. Hill, B. Malo, F. Bilodeau, S. Thériault, D. C. Johnson, and J. Albert

Communications Research Center, P.O. Box 11490, Station "H," Ottawa, Ontario K2H 8S2, Canada

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A simple method is described that permits the spectral response (spectral width, shape, and center resonant wavelength) of an optical waveguide Bragg grating to be controlled accurately in a prescribed manner. The control methodology consists of bonding the Bragg grating along the length of a mechanical support structure, which is then loaded with an appropriate force distribution. The function of the support structure is to transfer the strain induced by loading to the grating, thus modifying the grating's spectral response in accordance with the variation in effective optical pitch induced by the strain transfer. We design and demonstrate a support structure that provides independent control over the spectral width and center wavelength of a Bragg grating.

It is well known that the spectral response characteristic of an optical waveguide Bragg grating can be modified by the application of stress or by a change in temperature.[1–4] This attribute of optical waveguide Bragg gratings together with their narrow-band resonance response, small size, and light weight suggests their use as sensor elements for monitoring strain or temperature (the measurand is the shift in the Bragg grating resonance from an applied strain or a change in temperature).[5] Usually in sensor applications to monitor a structure's strain condition either we bond the Bragg grating sensor element to the surface of the structure or we embed it within the structure.

We can use the ease with which a Bragg grating can be closely coupled mechanically to a support structure as a means of controlling the properties of the Bragg grating.[2] In particular, because the deformation of simple beams and columns that is due to an applied load can be calculated accurately, such support structures are a suitable means to transfer known strain distributions to any optical waveguide Bragg grating that has been bonded to them. One can accomplish this conveniently by locating the Bragg grating along the surface (for example, but not exclusively) of a support structure that has been designed to have the desired strain distribution under known loading conditions.[4] Furthermore, by modifying the loading of the support structure, we can change the grating's spectral response in a wide variety of useful ways.

Using strain transfer from a support structure to a Bragg grating, we demonstrate in this Letter precise and reliable control of the optical bandwidth of the Bragg grating and the independent tuning of its center resonant wavelength by using a simple mechanical jig; then we discuss use of mounting-structure-loading techniques for the implementation of an optical waveguide Bragg grating frequency discriminator device.

In general, the Bragg grating control methodology that we propose consists of bonding the grating along (but not necessarily parallel to) the principal axis of a mechanical support structure, usually in the form of a beam or column, be it regularly or irregularly shaped. Typically the support structure is stressed by lateral loading (normal to its principal axis) to chirp the Bragg grating or by longitudinal loading (parallel to its principal axis) to vary the center resonant Bragg wavelength. Thus the support structure transfers its strain along the bonding curve of contact to the Bragg grating and changes the grating's spectral response in accordance with the variation in effective optical pitch induced by the strain transferred to the grating. By judicious design of the support structure, choice of the bonding curve of contact, and selection of the support-structure-loading strategy, a wide variability in Bragg grating spectral responses can be obtained.

We consider a horizontal, straight, uniform beam (length L) of constant rectangular cross section (moment of inertia of cross section about the neutral axis, I) made of homogeneous isotropic material characterized by Young's modulus, E. The bending moment $M(x)$ (with x measured along the principal axis of the beam) that is due to an applied load density $w(x)$ per unit length (which can be any combination of distributed or point forces) is given[6] by the relationship

$$\frac{\mathrm{d}^2 M(x)}{\mathrm{d}x^2} = w(x)\,.$$

This equation can be used to calculate the strain transfer from the beam under load $w(x)$, to a grating bonded to the beam. We assume implicitly that the beam is much stiffer than the fiber and consequently that the presence of the fiber does not alter significantly the response of the beam to the applied load $w(x)$. If we assume that the angle that the fiber makes with the plane of the neutral axis of the beam is small, the axial strain transferred to the fiber at a point x is proportional to $M(x)$ and to the distance $y(x)$ of the fiber from the neutral axis of the beam (i.e., the curve of contact) and is inversely proportional to EI.

For example, a linear chirp can be impressed on a Bragg grating by bonding the grating parallel to the principal axis $[y(x) = \text{constant}]$ of a uniform cantilever beam that has been anchored rigidly at one end ($x = 0$) and subjected to a point-force load $[w(x) = F_{\text{point}}\,\delta(x - L)]$ applied normal to its axis at the other ($x = L$). In this

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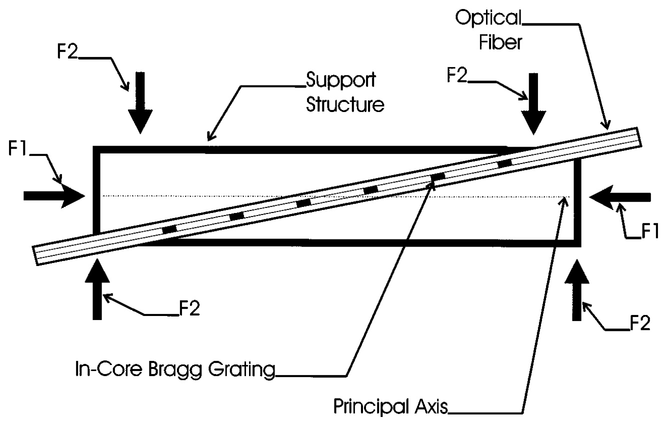

Fig. 1. Schematic diagram showing the point-force distribution applied to the beam structure and the placement of the Bragg grating device designed to induce a linear chirp in the grating.

case $M(x)$ increases linearly from zero at the point of application of the point force to a maximum at the anchor point.[3] In the linear elastic deformation limit the strain transferred to the Bragg grating begins at a low value (in close proximity to the loading point) and increases linearly to a value proportional to the loading and the distance from the load point, reaching maximum strain close to the cantilever anchor point. In this case the deflection $\Delta(x)$ of the beam is given by $\Delta(x) = F_{\text{point}} x^2 (3L - x)/6EI$, where $0 \le x \le L$. A linearly chirped Bragg grating exhibits a broadened spectral response.[3,7] But in the cantilever-based device the center resonant wavelength of the Bragg grating is also shifted to a value corresponding to the optical period of the Bragg grating at the center of the Bragg grating.[4] If the strain is positive (the Bragg grating has been elongated) the center resonant wavelength shifts to longer wavelengths. If the strain is negative (the Bragg grating is compressed), the shift is to shorter wavelengths. Ideally, it is desirable to control the degree of chirp (and thereby the spectral width) independently of the average Bragg grating period (and thereby the center wavelength). We have designed a special jig that permits the spectral width and the center wavelength of the Bragg grating to be controlled independently of each other.

The device, which is illustrated schematically in Fig. 1, has the optical waveguide Bragg grating filter bonded to the side of a uniform beam that has a rectangular cross section; the bonding geometry is chosen to yield a straight (line) curve of contact between the Bragg grating and the side of the beam under no-load conditions. The line of contact is angled with respect to the principal axis of symmetry of the beam as shown. Six counterbalanced point forces are applied symmetrically to the beam. The countervailing forces, F1, applied axially to the beam control the center wavelength of the Bragg grating, and the four equal forces orthogonal to the beam's principal axis, F2, control the chirp by applying a pure bending torque [$M(x) = \text{constant}$] in the central region of the beam between the two pairs of forces, F2. The chirping of the Bragg grating is a consequence of the symmetric, linear variation in displacement y of the fiber from the neutral plane of the beam. To tune the center resonant Bragg wavelength, the countervailing longitudinal forces acting on the beam are adjusted. To change the chirp of the Bragg grating, the lateral loading of the support structure is modified. It is apparent that the strain distribution transferred to the Bragg grating by F2 lateral loading is linear (compression on the side of the force pair closest to the beam center and tension on the opposite side). To compute the chirp, we use the following approximate relationship between the percentage of linear chirp and the other parameters of the Bragg grating, where λ_0 is the center wavelength, n_{eff} is the effective mode index, R is the reflectivity, and κ is the coupling coefficient[8]:

$$\%\,\text{Chirp} = \frac{50\lambda_0 |\kappa|^2 L}{n_{\text{eff}} \ln[(1 - R)^{-1}]} \,.$$

The Bragg grating that we used for our experiments was photoimprinted in the optical fiber (Corning SMF-28) by actinic radiation passing through a zero-order nulled phase mask.[9] The phase mask was fabricated by holographic photolithography. Hydrogen loading[10] was used before photoimprinting to enhance the photosensitive response of the optical fiber.[1] We carried out experiments by applying forces as shown in Fig. 1 to a 6-cm-long, 6 mm × 6 mm rectangular-cross-section beam with a 3-cm-long uniform Bragg grating bonded to the side of the beam and with the fiber axis at an 8.5° angle to the beam axis.

Figure 2 shows the measured spectral response of the Bragg grating in reflection for three values of linear chirp induced by the four transverse forces, F2. These forces give rise to the transfer of a centered strain distribution to the Bragg grating; therefore, the effect is purely to broaden the spectral response of the grating. In contrast, the longitudinal forces, F1, are used to tune the center wavelength. The values of percentage of linear chirp labeling the curves in the figure were computed with the aid of the formula given above by a Bragg grating refractive-index modulation amplitude of 6.6×10^{-5}. The results show that spectral broadening by a factor of at least 50 (8 nm/0.15 nm) is easily

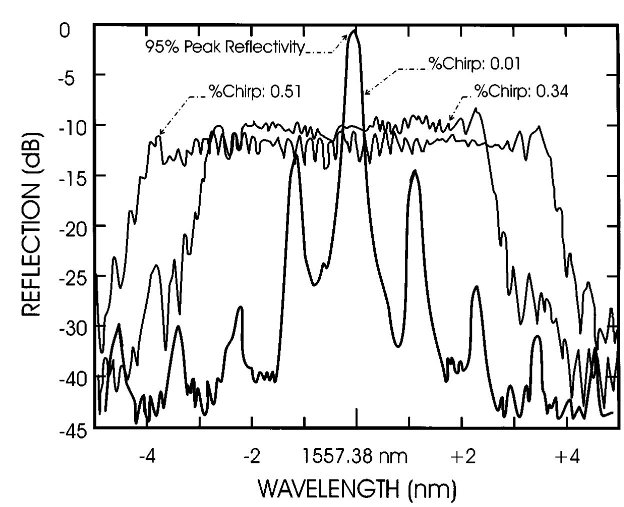

Fig. 2. Experimental reflectivity of the Bragg grating for three values of chirp.

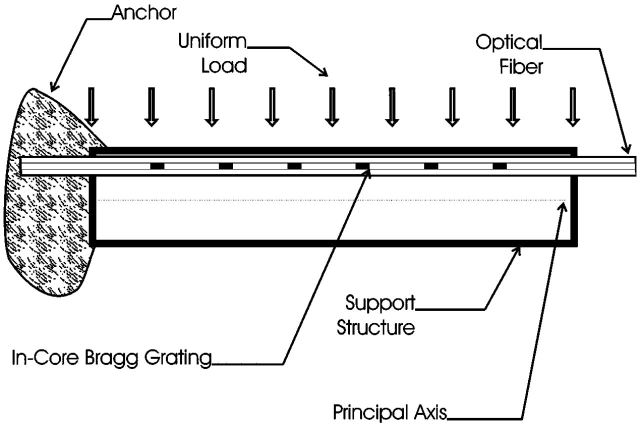

Fig. 3. Schematic diagram showing the uniform force distribution applied to the beam structure and the placement of the Bragg grating device to induce a quadratic chirp in the grating.

obtained by strain transfer for the case of a 3-cm-long uniform Bragg grating. We note that the low-chirp spectral response exhibits satellite peaks 15 dB lower with respect to the central peak. The satellite peaks are the result of a small systematic periodic error in the mask used to photoimprint the Bragg grating and are not relevant to the control of the spectral width of the Bragg grating. The noiselike structure in all three curves can probably be reduced by substituting an apodized Bragg grating in place of the uniform grating we used.

Figure 3 illustrates a loading strategy that is simple to implement and useful for inducing a quadratic chirp in an in-fiber Bragg grating and obtaining thereby a linear discriminator wavelength response. Here $x = 0$ at the free end of the beam, $y(x) =$ constant, and $w(x) =$ constant, yielding, by integration of the bending moment equation above, $M(x) = wx^2/2$ and therefore a quadratically increasing strain along the line of contact to a maximum at the beam anchor point, $x = -L$. See Fig. 5 of Matsuhara *et al.*[11] for the theoretical spectral response of a grating with a quadratic chirp.

In summary, we have fabricated a novel variable-spectral-response optical waveguide Bragg grating filter device. The filter is useful for general signal-processing applications, for example, in dispersion compensation.[12] The method that we used is general and lends itself to synthesizing many useful and variable Bragg grating responses.

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