Material Properties Measurement

Study on Dynamic Strain Measurements using Improved Bonding Fiber Bragg Grating (IBFBG)
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ABSTRACT

This study suggests an improved bonding method for a surface-mounted fiber Bragg grating (FBG) strain sensor to largely reduce the interference from the surrounding cement, and to maintain the sensitivity of an intact FBG. The numerical modelings based on the coupled mode theory were carried out to obtain the reflected spectra of an FBG. The parameter studies for the influences of strain field gradients on measured voltage signals are demonstrated to show the advantages of the IBFBG.

INTRODUCTION

Since the demonstration of the formation of permanent gratings in an optical fiber by Hill et al. in 1978 [1, 2], fiber Bragg grating (FBG) sensors have been widely used in many applications [for example, 3, 4]. FBG sensors offer important advantages, such as electrically passive operation, EMI immunity, high sensitivity, and multiplexing capabilities. However, in applications of strain measurements, the current practice of surface-bonding an FBG strain sensor (traditional bonding fiber Bragg grating, this study simply call it as the TBFBG) is to distribute cement on all its grating zone [for example, 5]. The apparent result is that the obtained reflected spectrum from the TBFBG is the outcomes of a strain distribution of the targeted structural surface along the glued grating zone [6-14]. Researchers have used such properties to detect the characteristics of strains along the grating zone to provide a distant warning of damage or cracks [for example, 15-17]. Still, when using the TBFBG strain sensor, the distribution of axial strain along the axis of its glued grating zone is difficult to be validated directly (or reasonably) with a commonly used strain sensor, a resistance strain gauge. The reason is that an FBG strain sensor generally has its grating zone with a length about 10 mm and a diameter about 0.125 mm, however, the commonly used resistance strain gauge has an area of about 1 mm × 1 mm. Based on this, an FBG strain sensor is more likely a line sensor compared with the resistance strain gauge a point sensor. In addition, TBFBG sensors are usually not reusable, owing to the difficulty of confirming the intactness of the glued grating zone in all removal processes.

This study suggests an improved bonding fiber Bragg grating (IBFBG) strain sensor. On the contrary, the improved bonding method is to distribute cement (along the optic fiber) only on the two ends of a uniform-pitch grating zone, and all the grating zone is free of cement. Such improved bonding practice always leads to a reflected spectrum that corresponds to the uniform distribution of the average strain over the glued free grating zone. As compared to the TBFBG, the IBFBG is more sensitive and allows higher reusability since its grating zone is left intact.

A sufficient amount of pre-strain is needed for an IBFBG to retain the linear function between its axial strain and its Bragg wavelength shift during axial tension and compression. In addition, when the IBFBG is used on the compressive side of bending, the longitudinally directed IBFBG is shortened in the lengthwise direction of the glue-free grating zone. Surely this situation creates a larger compressive strain value in the IBFBG than that value on the targeted structural surface. However, the differences between the two compressive strains (of the targeted structural surface and IBFBG) can be neglected except in the cases of very large curvatures.

The most important advantage of the IBFBG strain sensor (over the TBFBG) is the uniform distribution of the average strain. In other words, the average strain is the exact parameter obtained from the IBFBG. For most engineering applications, except for the case that a concentrated loading directly acts on the sensor, strain fields that vary linearly in the length about 10 mm (the length scale of a grating zone) are common, and the parameter (average strain) obtained from the IBFBG can be regarded as the targeted surface strain at the middle point under the glued free grating zone. The reflected spectra from the IBFBG are always undistorted (even at larger strains), and the dynamic
calibrations of an IBFBG by using a common resistance strain gauge (with an area of about 1 mm × 1 mm) are reasonable.

This study starts with numerical computations in which the reflected spectra of both the uniform pitched TBFBG and IBFBG under the linear varied strain fields are obtained. The layout of the wavelength interrogation system used is also taken into account to model the measured voltage signals. From this numerical study, the influences of strain field gradients on measured voltage signals of the TBFBG and IBFBG are understood, a quantitative comparison between TBFBG and IBFBG is made, and then the advantages of the IBFBG strain sensor are shown.

EXPERIMENT LAYOUT AND ITS NUMERICAL MODELINGS

This section explains the experiment layout that is used to obtain dynamic strain induced voltage signals. The wavelength interrogation system used starts from a broadband light source, to a filter, to an FBG sensor, to a photodiode (PD), and finally to an oscilloscope. The received photo-current from the photodiode is converted into a voltage signal by a transimpedance amplifier (TIA). In addition, the outlines of the numerical modelling are given.

**Figure 1 - Layout of the wavelength interrogation system.**

**EXPERIMENT LAYOUT**

Figure 1 shows the layout used to carry out wavelength interrogation for both the FBG strain sensors, the IBFBG and TBFBG. For each FBG strain sensor, this study employs an FBG filter as a wavelength-to-amplitude converter [18-20]. A 1×3 splitter is used in which the two outputs are respectively for the IBFBG and TBFBG strain sensors, and one output for the reference. All measurements are obtained from filtered signals after division by the referenced signals to avoid variation from the optical power source. The optical fibers are single mode (diameter 125 μm) fibers manufactured by FIBERCORE, England. The resistance strain gauge is the type KFG-1N-120-C1-11L2M2R, from KYOWA, Japan. The glue used for surface-mounting the FBG’s and the resistance strain gauge is the cyanoacrylate instantaneous adhesive, type CC-33A, from KYOWA. An oscilloscope (WaveSurfer 64Xs, from LeCroy) with a sampling rate of 2.5 MHz is used in this study.
Transient dynamic vibrations are aroused by impacting a free-falling steel ball on a steel cantilever. Figure 2 displays the steel cantilever, in which both the IBFBG and TBFBG are attached in the closest distance between their axes of fibers—that is, diameter of a optic fiber (0.125 mm) - to measure the longitudinal strains along almost the same line, and the resistance strain gauge is bonded symmetrically to the underside from both the FBGs to serve as a strain reference. In such an arrangement, comparisons between the IBFBG and TBFBG can be made, and the reference strains obtained from the resistance strain gauge are used to demonstrate that dynamic calibrations of an IBFBG by using a resistance strain gauge are reasonable. In addition, for the authors’ dynamic signal measurements, its maximum frequency of interest is always under the order of 0.1 MHz. Such frequency is surely within the operating bandwidth of a commonly used photodiode.

**THEORY AND FORMULATIONS**

Fiber Bragg gratings are produced by exposing an optical fiber to a spatially varying pattern of ultraviolet intensity. The distribution of the effective refractive index $n_{\text{eff}}(z)$ along an FBG before heating and straining is described as [21]

$$n_{\text{eff}}(z) = n_0 + \delta n(z) \cdot \{ h + \cos[\frac{2\pi}{\Lambda(z)} z] \}$$  \hspace{1cm} (1)

where $z$ is the distance along the fiber longitudinal axis, $n_0$ is the effective refractive index of the fiber before UV exposure, $\delta n(z)$ is the envelope of effective index change, $h$ is the background component of the effective index change, and $\Lambda(z)$ is the nominal period of the grating.

Except for the case that a concentrated loading directly acts on the sensor, the linear varied strain distribution on the length scale of an FBG is a suitable approximation. The linear varied strain field is

$$\varepsilon(z,t) = \varepsilon_0 \cdot (1 + s_1 \cdot z)$$  \hspace{1cm} (2a)

where $\varepsilon_0 \cdot s_1(t)$ is the gradient of the strain field, $\varepsilon_0(t)$ is the strain at the location of $z = 0$, and $t$ is time. Because of the linear varied strain field $\varepsilon(z,t)$ shown in (2a), the initially uniform fiber grating with period, say, $\Lambda_0$ is transformed to the strained period $\Lambda_{\text{strained}}(z)$, and the index change due to strains should be taken in consideration. In the following, the strained periods are separately described for the TBFBG and IBFBG.
For the TBFBG, grating periods non-uniformly change along its axis due to the strain field (2a). The strained length in the \( n \)th period, between the two initial locations \( z = (n-1)\Lambda_0 \) and \( z = n\Lambda_0 \), can be represented by

\[
\Lambda_{\text{strained}}(z) \in [(n-1)\Lambda_0, n\Lambda_0)] = \Lambda_0 \cdot [1 + \varepsilon_0 \cdot (1 + \frac{\delta n}{2} \cdot \Lambda_0 \cdot (2n - 1))]  \tag{2b}
\]

where \( n = 1, 2, 3, \ldots \). This expression (2b) is obtained by integrating the strained lengths between \( z = (n-1)\Lambda_0 \) and \( z = n\Lambda_0 \), and is used to consider the strain induced period changes for differential lengths located between \( z = (n-1)\Lambda_0 \) and \( z = n\Lambda_0 \).

For the IBFBG, by contrast, its grating periods uniformly change along its axis. The uniform strain on the IBFBG due to the strain field (2a) is

\[
\varepsilon_0 \cdot (1 + \frac{\delta n}{2} \cdot l). \tag{2c}
\]

On the other hand, the index changes due to strains should be considered [22-24]. In the traditional bonding method, due to shrinkage from the cement used along the full grating length, an FBG subjects to strain fields far more complex than the pure axial strain. Evidently, the improved bonding method is better than the traditional method to reduce the complicated strain from cement. However, for simplicity, the TBFBG and IBFBG are regarded as in the same pure axial strain field in this study.

According to [22-24] the axial strain induced index change \( \frac{dn_{\text{eff}}}{d\varepsilon} \) (or due to the photoelastic effect) is in value of -0.047125. Here \( n_{\text{strained}} \) is used to denote the index after straining, that is,

\[
n_{\text{strained}} = (n_0 + h \cdot \Delta n) \cdot (1 + \varepsilon_0 \cdot \frac{dn_{\text{eff}}}{d\varepsilon}) = (n_0 + h \cdot \Delta n) \cdot (1 - 0.047125 \cdot \varepsilon) \tag{2d}
\]

where the unstrained index \( (n_0 + h \cdot \Delta n) \) and the axial strain \( \varepsilon \) are respectively described at (1) and (2a).

The coupled-mode theory is a good tool for obtaining quantitative information about the diffraction efficiency and spectral dependence of fiber gratings [for example, 21, 25-33]. The resulting equations can be written as

\[
\frac{dA}{dz} = i\beta A + i\kappa B \tag{3a}
\]

\[
\frac{dB}{dz} = -i\beta B - i\kappa A \tag{3b}
\]

where \( A(z, \varepsilon, \lambda) \) and \( B(z, \varepsilon, \lambda) \) are respectively the incident and reflected complex amplitude, \( \lambda \) is the wavelength of light, \( \beta \) is the self-coupling coefficient defined as

\[
\beta \equiv \frac{2\pi}{\lambda} \cdot n_{\text{strained}} - \frac{\pi}{\Lambda_{\text{strained}}} \tag{4a}
\]

in which \( \Lambda_{\text{strained}} \) refers to (2b) and (2c), and \( n_{\text{strained}} \) refers to (2d). \( \kappa \) is the ac coupling coefficient defined as

\[
\kappa \equiv \frac{\pi}{\lambda} \cdot \Delta n \tag{4b}
\]

If the length of the fiber grating is \( l \), for example, from \( z = 0 \) to \( z = l \), the reflectance \( R(\varepsilon, \lambda) \) and transmittance \( T(\varepsilon, \lambda) \) as a function of wavelength \( \lambda \) can be found by forming

\[
R(\varepsilon, \lambda) = \left| \frac{B(z = 0, \varepsilon, \lambda)}{A(z = 0, \varepsilon, \lambda)} \right|^2 \tag{5a}
\]
\[ \begin{align*}
T(\epsilon, \lambda) &= \left| \frac{A(z = l, \epsilon, \lambda)}{A(z = 0, \epsilon, \lambda)} \right|^2 \\
\end{align*} \] (5b)

According to the experiment layout shown in Fig. 1, it is assumed that the spectrum of light from broadband source is \( S(\lambda) \); the FBG filter has its transmission spectrum of \( F(\lambda) \); the FBG strain sensor has its reflected spectra of \( R(\epsilon, \lambda) \); and the photosensitivity of the photodiode is \( P(\lambda) \). Then the voltage signals \( V(\epsilon) \) recorded at an oscilloscope is expressed as

\[ V(\epsilon) = k \int_{\lambda_1}^{\lambda_2} S(\lambda) \cdot F(\lambda) \cdot R(\epsilon, \lambda) \cdot P(\lambda) \cdot d\lambda \] (6)

where \( k \) is a proportional constant to transfer optical power induced current to the voltage in the photodiode used, and \( \lambda_1 \) and \( \lambda_2 \) are the two extreme wavelengths in the bandwidth in which the photodiode detects. Those quantities of \( k, S(\lambda), F(\lambda) \) and \( P(\lambda) \) in the integration (6) are kept the same during a dynamic strain measurement. Only the reflected spectrum \( R(\epsilon, \lambda) \) from the FBG strain sensor is related to the measured strain distribution \( \epsilon(z, t) \) when disturbances continue.

**Numerical Scheme**

Although there exists softwares, such as RSOFT, to compute the reflected or transmitted spectrum of an FBG; however, for convenience of parameter studies the authors have to develop a computer program (using language of the FORTRAN) to calculate the spectrum. This study focuses on how the gradients of a linear varied strain field influence voltage signals \( V(\epsilon) \) recorded at an oscilloscope. However, see the integration (6), voltage signals \( V(\epsilon) \) depend on reflected spectra \( R(\epsilon, \lambda) \) from an FBG strain sensor. Thus, this study should start with a numerical scheme for solutions of the coupled ordinary differential equations (3) with variable coefficients along \( z \) according to (1), (2) and (4). Then the computation for the reflectance \( R(\epsilon, \lambda) \) at a wavelength according to (5a) can be achieved. Finally, the reflectance for a range of wavelengths are obtained to complete a simulated FBG reflected spectrum.

From the coupled ordinary differential equations (3), its vector form is written as

\[ \frac{d}{dz} \begin{bmatrix} A \\ B \end{bmatrix} = \begin{bmatrix} iB & i\kappa \\ -i\kappa & -iB \end{bmatrix} \begin{bmatrix} A \\ B \end{bmatrix} \] (7)

In the follows, \( \mathbf{V} \) and \( \mathbf{M} \) are defined as \( \begin{bmatrix} A \\ B \end{bmatrix} \) and \( \begin{bmatrix} iB & i\kappa \\ -i\kappa & -iB \end{bmatrix} \), respectively. Then for a sufficiently small increment \( \Delta z \), the corresponding increment \( \Delta \mathbf{V} \) can be calculated by

\[ \Delta \mathbf{V} = \Delta z \cdot \mathbf{M} \cdot \mathbf{V} \] (8)

Consider the situation that light incidents from only one side of an FBG. As shown in Fig. 3, the full length \( l \) of an FBG is discretized as \( N \) sections, and those nodes are denoted consecutively from the node number 0 (where \( z = 0 \)) to the node number \( N \) (where \( z = l \)). It is also assumed that light incidents from the node 0. In the follows, \( \mathbf{V}_n \) and \( \mathbf{M}_n \) denote the vector and the matrix at the location with the node number \( n \).
To compute the reflectance for a wavelength $\lambda$, see (5a), the calculation should go backward from the node number $N$, for example, $A_N(1,0)$ and $B_N(0,0)$, to obtain $A_0(0,0)$ and $B_0(0,0)$ at the node number 0. Some details are listed below [for example, 21, 25-33].

$$\mathbf{V}_n = \mathbf{V}_{n+1} - \Delta \mathbf{V}_{n+1} = \mathbf{V}_{n+1} - \mathbf{M}_{n+1} \cdot \mathbf{V}_{n+1} \cdot \Delta z = \left( \mathbf{I} - \Delta z \cdot \mathbf{M}_{n+1} \right) \cdot \mathbf{V}_{n+1} = \mathbf{T}_{n+1} \cdot \mathbf{V}_{n+1}$$

(9)

where $\mathbf{I}$ is the 2x2 identity matrix, and $\mathbf{T}_{n+1} = \mathbf{I} - \Delta z \cdot \mathbf{M}_{n+1}$.

Therefore,

$$\mathbf{V}_0 = \prod_{i=1}^{N} \mathbf{T}_i \cdot \mathbf{V}_N$$

(10)

A reflectance at a wavelength $\lambda_s$ is obtained as stated above and this process is repeated from wavelengths $\lambda_s$ to $\lambda_s$ with a step wavelength, say, $\Delta \lambda = \frac{\Delta \lambda_0}{1000}$, to complete a reflected spectrum, where $\Delta \lambda_0$ is the bandwidth between the first zeros on either side of the maximum reflectivity for a uniform fiber grating [21]. The related quantities are listed as follows.

$$\Delta \lambda_0 = 2 n_0 \Lambda_0 \left[ \frac{\delta n}{n_0} \sqrt{1 + \left( \frac{2 n_0 \Lambda_0}{\delta n \cdot l} \right)^2} \right]$$

(11)

where $n_0$ and $\delta n$ refer to (1), $\Lambda_0$ is the uniform grating period before straining, and $l$ refers to Fig. 3. In computations, both the wavelengths $\lambda_s$ and $\lambda_s$ should cover the dominant parts of reflected spectra.
Figure 4 shows the computed reflected spectrum (solid line) with $l=2 \text{ mm}$, $s_1=0$, $\Lambda_0=500 \text{ nm}$, $n_0=1.482$, $\delta n=10^{-3}$, and $h=1$, that is almost the same as its corresponding exact solution (dashed line) for a uniform fiber grating. Such check demonstrates the validity of the computed reflected spectra.

**PARAMETER STUDIES AND THEIR RESULTS**

In the integration (6), the measured voltage signals are related to an integration from wavelengths $\lambda_1$ to $\lambda_2$. The integrand can be divided into two parts: $S(\lambda) \cdot F(\lambda) \cdot P(\lambda)$ and $R(\varepsilon, \lambda)$. For convenience, the first part is defined as $L(\lambda)$,

$$L(\lambda) \equiv k \cdot S(\lambda) \cdot F(\lambda) \cdot P(\lambda) \quad (12)$$

In general, the wavelength interrogation system used (see Fig. 1) transfers a wavelength shift to an optical power variation. Such transformation is linear when the dominant portion of $R(\varepsilon, \lambda)$ is located in the bandwidth between wavelengths $\lambda_a$ and $\lambda_b$, where $L(\lambda)$ linearly increases or decreases. That is,

$$L(\lambda) = L_0 + s_2 \cdot (\lambda - \lambda_a) \quad , \quad \lambda \in [\lambda_a, \lambda_b] \quad (13)$$

where $L_0$ is the value of $L(\lambda=\lambda_a)$. $s_2$ is the slope for the linear variation part, $\lambda_1 < \lambda_a < \lambda_b < \lambda_2$. In addition, it is assumed that wavelengths $\lambda_a$ and $\lambda_b$ are compatible with the bandwidth for equation (13) because of adjustments before measurements.

Furthermore, the interval $\lambda \in [\lambda_1, \lambda_2]$ of the integration (6) can be divided as three parts, that is,

$$\int_{\lambda_1}^{\lambda_2} \quad \int_{\lambda_1}^{\lambda_a} + \int_{\lambda_a}^{\lambda_b} \quad \int_{\lambda_b}^{\lambda_2}$$

in which for simplicity the same integrands as in (6) are omitted in the three parts. Both the integrations at the two ends, from $\lambda_1$ to $\lambda_a$ and from $\lambda_b$ to $\lambda_2$, are almost constant, and the sum of these two integrations is denoted to be $V_B$. In addition, the integration from $\lambda_a$ to $\lambda_b$ is denoted to be $\Delta V(\varepsilon)$.

$$V_B = \int_{\lambda_1}^{\lambda_a} L(\lambda) \cdot R(\varepsilon, \lambda) d\lambda + \int_{\lambda_a}^{\lambda_b} L(\lambda) \cdot R(\varepsilon, \lambda) d\lambda \quad (14a)$$

$$\Delta V(\varepsilon) = \int_{\lambda_a}^{\lambda_b} L(\lambda) \cdot R(\varepsilon, \lambda) d\lambda \quad (14b)$$

Thus, the sum of $V_B$ and $\Delta V(\varepsilon)$ is the measured voltage signal $V(\varepsilon)$.

$$V(\varepsilon) = V_B + \Delta V(\varepsilon) \quad (15)$$

**DISTORTION**

Based on (6) and (12) to (15), this study defines the index distortion:

$$\text{distortion} \equiv \frac{V(\varepsilon(z)=10^{-6}) - V(\varepsilon(z)=0) - \varepsilon_{\text{ave}}}{\varepsilon_{\text{ave}} \cdot 10^{-6}} \quad (16)$$
where $\varepsilon_{\text{ave}}$ is the average strain of the targeted structural surface under the length of an FBG strain sensor. To study the influences of a distorted reflected spectrum on a measured voltage signal, the index distortion defined in (16) is based on the zero distortion situation in which the terms
\[
\frac{V(\varepsilon(z)) - V(\varepsilon(z) = 0)}{V(\varepsilon(z) = 10^{-6}) - V(\varepsilon(z) = 0)} = \frac{\varepsilon_{\text{ave}}}{10^{-6}}.
\]
In short, the index distortion is zero when the measured changes in voltage signals are proportional to the corresponding strains.

For example, Figs. 5 and 6 respectively demonstrate the reflected spectra from the TBFBG and the IBFBG., in which $n_0=1.482$, $\delta n = 7 \times 10^{-4}$, $l=3$ mm, and $h=1.0$. Figure 5, for the TBFBG, shows apparent distortions of the spectra under the strain fields with gradients $\varepsilon_0 \delta_1$ from 0 to $8000 \times 10^{-6}$ cm$^{-1}$ and $\delta_1 = 4.0$ cm$^{-1}$. However, Fig. 6 for the IBFBG under the same strain fields, its spectra mainly display the wavelength shifts due to the average strains. The corresponding voltage signals based on filter functions of $L(\lambda) = \frac{1}{12} (\lambda - 1480)$ and $L'(\lambda) = 1 - \frac{1}{12} (\lambda - 1480)$ are respectively shown in Figs. 7 and 8. Figures 7 and 8 show not only the voltage signals but also its corresponding values of index distortion (see (16)), in which the TBFBG strain sensor has evident nonlinear (concave upward and downward, respectively) relations between voltage signals and average strains. Still, the values of index distortion (see its definition (16)) at $\varepsilon_{\text{ave}} = 0$ cannot be determined. Especially, in Fig. 8, the voltage signals of the TBFBG by using the filter function $L(\lambda) = 1 - \frac{1}{12} (\lambda - 1480)$ do not decrease, until average strain of 0.002, as the straining increases. However, compared with the TBFBG, the IBFBG strain sensor always has negligible distortions in its reflected spectra. The phenomenon of non-negligible distortions (or non-negligible values of the index distortion) demonstrates that changes of voltage signals from the TBFBG cannot be regarded as proportional to the corresponding average strains of the strain fields. Based on this non-proportionality, one cannot use the common resistance strain gauge, as a reference of the average strain, to carry out strain calibrations for the voltage signals from the TBFBG. By contrast, the very small (or negligible) distortions of the reflected spectra from the IBFBG (shown in Figs. 6, 7 and 8) demonstrate the validity of taking the average strain as its representative parameter.
Figure 5 - Distortions of the TBFBG’s spectra under the strain field with gradients $\varepsilon_0 s_1$ from 0 to $8000 \times 10^{-6}$ /cm, in which the dashed line $L(\lambda) = \frac{1}{12} (\lambda - 1480)$ and dashed dot line $L(\lambda) = 1 - \frac{1}{12} (\lambda - 1480)$ are the filter functions used to compute the corresponding voltage signals.

Figure 6 - The negligible distortions of the IBFBG’s spectra under the same strain field for the TBFBG shown in Fig. 5, in which the dashed line and dashed dot line are the filter functions (see the caption of Fig. 5) used to compute the corresponding voltage signals.
Figure 7 - Using the filter function $L(\lambda) = \frac{1}{12} (\lambda - 1480)$, the corresponding voltage signals and the values of the index distortion for the TBFBG and the IBFBG are shown.

Figure 8 - Using the filter function $L(\lambda) = 1 - \frac{1}{12} (\lambda - 1480)$, the corresponding voltage signals and the values of the index distortion for the TBFBG and the IBFBG are shown.
In order to carry out the parameter studies, ranges and typical values of related parameters are listed in the following [34-37].

(a) The grating length $l = 5$ to 10 mm.

Figure 9 - The spectrum of the TBFBG strain sensor has a larger distortion when its index change $\delta n$ is smaller ($\delta n = 3 \times 10^{-4}$). However, the IBFBG has its spectra shifted but negligible distortion.

Figure 10 - The spectrum of the TBFBG strain sensor with a longer grating length has a larger distortion than the one has a shorter grating length.

Ranges and typical values of the related parameters

In order to carry out the parameter studies, ranges and typical values of related parameters are listed in the following [34-37].

(a) The grating length $l = 5$ to 10 mm.
(b) The effective refractive index of the fiber before UV exposure $n_0 = 1.482$.
(c) The initial, or unstrained, uniform grating period $\Lambda_0 = 400$ to 500 nm.
(d) The constant effective index change $\delta n = 10^{-4}$ to $10^{-2}$.
(e) The background component of the effective index change $h = 1$.

RESULTS OF THE PARAMETER STUDIES

To understand the influences of strain field gradients $\varepsilon_0 s_1$ (in strain/length) on the distortion of reflected spectra from an FBG strain sensor, Figs. 9 and 10 show the IBFBG almost only has wavelength shift in its spectra; however, the TBFBG has larger distortion in its spectra and the behavior depends largely on parameters: the index change $\delta n$ and the grating length $l$.

Figure 9 demonstrates that the TBFBG’s reflected spectrum distorts more significantly for a smaller value of $\delta n = 3 \times 10^{-4}$ than that of $\delta n = 7 \times 10^{-4}$, under a strain field with $\varepsilon_0 = 1000 \times 10^{-6}$ and $\varepsilon_0 s_1 = 4000 \times 10^{-6}$/cm. Considering the same strain field, Fig. 10 makes comparison between the spectra from two grating lengths $l = 5$ and 10 mm. The TBFBG strain sensor with a longer grating length $l = 10$ mm has larger distortions than the shorter one.

DISCUSSIONS AND FUTURE WORKS

(1) This research conducts preliminary study for the influences of strain field gradients on distortions of reflected spectra from an FBG strain sensor and its voltage signals. In those parameter studies, one always sees that the suggested IBFBG (the improved bonding FBG) surface-mounting strain sensor is a nice choice to avoid distortions of reflected spectra.

(2) From the computations of the index distortion (see (16)), the relation between those changes of voltage signals from the TBFBG (the FBG with the conventional bonding method) surface-mounting strain sensor and the corresponding average strain shows non-negligible deviations from a linear relationship. However, the IBFBG strain sensor has an almost linear relation for that. Therefore, for the IBFBG strain sensor, dynamic strain calibrations using a common resistance strain gauge are reasonable.

(3) Because of distortions in the TBFBG’s spectra, its voltage signals contain not only effects from the average strains, but also effects from the gradients of strain fields. Evidently, how to obtain the average strains and the gradients of strain fields from messages of distorted reflected spectra is one of future works for the authors.

(4) To clarify how the gradients of strain fields influence measured voltage signals, a more general parameter study is needed in the near future. In addition, experimental works to demonstrate the phenomena shown in the numerical computations of this study is also one of the authors’ future works.

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