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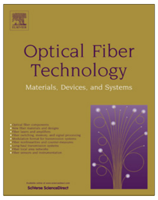

Regular Articles

Spectral characterization of polarization dependent loss in fiber Bragg grating under local pressure and the analysis of secondary peak

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ABSTRACT

In this paper, a study of the spectral characterization of polarization dependent loss (PDL) in fiber Bragg grating (FBG) under local pressure is presented and the evolution of the secondary peak is analyzed. The effects of the load magnitude, loaded length and loaded position on the amplitude and wavelength of the created secondary peak are investigated in detail. The numerical simulation based on the modified transfer matrix method is used to calculate the transmission and PDL response of the FBG. The theoretical analysis and numerical simulation demonstrate that the loaded length and load amplitude have significant effect on the characterization of the secondary peak. The results show that there is the potential in distributed FBG transverse load sensing by tracking the secondary peak of PDL variation.

1. Introduction

The sensor based on a fiber Bragg grating (FBG) can satisfy the requirement in sensing a number of physical parameters such as strain or temperature, which changes the center wavelength of the reflected spectrum when the sensing parameters cause grating effective index or grating period variation [1–3]. They provide significant advantages such as small size, geometric flexibility and distributed sensing possibilities [4–6]. Up to now, for most applications of FBGs, the research efforts have concentrated on the features of the spectral behavior of the gratings.

In the case of transverse load, stress-induced birefringence effects will cause the unique Bragg grating condition to break down and even produce two distinct Bragg wavelengths [7]. Actually this stress induced birefringence is hardly perceived in the amplitude spectral response of the grating due to its low sensitivity [8]. However, it will lead to significant polarization parameters such as polarization dependent loss (PDL), differential group delay (DGD) and the first Stokes parameter (s_1) values [9] within the grating, which can provide more effective information and therefore lead to the potential development of new types of FBG-based optical sensors [10–12]. We have presented a new method for real-time transverse force sensor based on the measurement of the polarization properties of a uniform FBG written into standard single mode fiber [12]. Lammens et al. *reported a practical work towards the accurate detection of small transverse strains using PDL technique in optical fiber Bragg gratings* [13].

There has also been investigations on local perturbations in fiber Bragg gratings by heating or pressing a short segment of the grating. In [14] the heated segment was <1% of the grating length and it was observed a transmission window in the reflected spectrum relating the heated region in a chirped FBG. In [15], the authors presented an experimental and theoretical study of the spectral characterization and shaping of FBGs by applying a transverse force to a small grating section (<1% of the grating length). These reports explained that when the FBG is subjected to a local transverse load, the pressed section will cause a phase shift and introduce a transmission notch within the bandwidth of the FBG spectrum, which acts like a phase-shifted grating. The transmission notch will be located at the center of the bandwidth if the phase-shift is equal to π. And it walks to longer wavelengths until that the original spectrum is recovered, then a new period of shaping effects is initiated.

However, when the affected region is getting longer, it becomes quite different from both the case with whole grating length pressed, as reported in [7–8,10–12], and the case with very small section pressed, as reported in [14–16]. For transmission spectrum, the affected region was 20% of the grating length creating a secondary peak at wavelength longer in the reflectance spectrum was reported in [17]. Researches in [18] reported that when the affected region was 8% of the grating length for a grating with square index profile, an intra grating structure with Bragg wavelength longer than the original one was observed. In [16], the

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authors considered both weak and strong apodized unchirped gratings with a perturbed region $l > 10\%$ of the grating length and observed that, apart from the main peak, a secondary peak at wavelength longer than the original one is created. This secondary peak corresponds to the intra grating structure produced by the pressure element, and its position is a function of the applied force [18].

In the above studies, however, the effects of the load magnitude, loaded length and loaded position of the grating on the amplitude and position of this secondary peak are not discussed in detail. And, to the best of our knowledge, no work has been reported concerning the PDL characterization with respect to the secondary peak of locally pressed FBG. More recently, in [19], the authors presented the evolution of the PDL response of a locally pressed FBG. In their paper, they discussed two cases: the case that 2.5% of grating length affected with load magnitude ranging from 0 to 25 N and the case that load magnitude of 5 N with load length ranging from 0 to the whole grating length. However, the secondary peak was not observed. So the condition to produce this secondary peak needs to be investigated.

Since the FBG is always under local transverse load in some practical applications. Establishing and perfecting the PDL response of the FBG under local load is thus beneficial in FBG transverse load sensing, with the aim of developing a sensor that tracks the PDL variation as a function of the applied local load. Therefore the PDL characterization of locally pressed FBG in this case needs additional investigation.

Motivated by the lack of such a study, in this paper, the relationship of the load magnitude, the loaded length and the loaded position of the grating to the transmission and PDL responses are studied, and then their influences on the amplitude and wavelength of the secondary peak are completely analyzed and presented. The wavelength dependency of PDL evolution on the local transverse load is numerically simulated by utilizing a modified transfer matrix method. Through numerical simulations, it is shown that the secondary peak curves can be strongly affected by the load magnitude and the loaded length.

2. Theoretical model

When the FBG is subjected to a local transverse load, the difference between the effective refractive indices of the two orthogonal modes of the fiber within the loaded region will be produced. For simplicity the direction of the transverse load is assumed as y (fast axis), another direction perpendicular to y-axis is x direction (slow axis), z is along the fiber axial direction, as shown in Fig. 1.

The refractive index changes within the loaded zone is given by [20],

$$(\Delta n_{\text{eff}})_x = -\frac{n_{\text{eff}}^3}{2E}\{(p_{11} - 2\upsilon p_{12})\sigma_x + [(1-\upsilon)p_{12} - \upsilon p_{11}](\sigma_y + \sigma_z)\} \tag{1a}$$

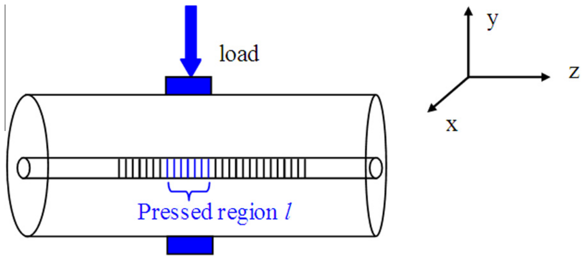

Fig. 1. Schematic diagram of a FBG subjected to local transverse load.

$$(\Delta n_{\text{eff}})_y = -\frac{n_{\text{eff}}^3}{2E}\{(p_{11} - 2\upsilon p_{12})\sigma_y + [(1-\upsilon)p_{12} - \upsilon p_{11}](\sigma_x + \sigma_z)\} \tag{1b}$$

where E and υ are the Young's modulus and Poisson's coefficient of the optical fiber respectively, (for typical optical fiber $E = 74.52$ GPa, $\upsilon = 0.17$, $p_{11} = 0.121$, and $p_{12} = 0.270$). σ_x, σ_y and σ_z are the stress components in the grating in the x, y and z directions, respectively.

Purely compression load on a glass cylinder could be modeled as a line force since both optical fiber and compression platform are hard media [19]. Since the length of a FBG is much longer than the diameter of the fiber, it is reasonable to assume the loading situations to be contained in a single plane. In our simulations, the test FBG is fixed at both ends and thus the FBG is under a loading state of plane strain ($\varepsilon z = 0$) to simplify the loading in the fiber. The stress state of the loaded section of grating can be found from the plane strain elasticity solution, given by [8,20,21]:

$$\sigma_x = \frac{2F}{\pi Dl}, \quad \sigma_y = -\frac{6F}{\pi Dl}, \quad \sigma_z = \upsilon(\sigma_x + \sigma_y) \tag{2}$$

where D is the fiber diameter, F is the applied force, and l is the length of the region under stress.

Due to the birefringence, the x and y modes undergo different couplings through the grating. The total transmitted signal is, therefore, the combination of the x and y mode signals. In a Cartesian coordinate system whose reference axes match the FBG eigenmodes, the Jones matrix of the grating is diagonal and the Jones vector of the transmitted signal is then,

$$\begin{bmatrix} E_{o,x} \\ E_{o,y} \end{bmatrix} = \begin{bmatrix} t_x & 0 \\ 0 & t_y \end{bmatrix} \begin{bmatrix} E_{i,x} \\ E_{i,y} \end{bmatrix} = \begin{bmatrix} t_x E_{i,x} \\ t_y E_{i,y} \end{bmatrix} \tag{3}$$

$(E_{ix}, E_{iy})^T$ is the Jones vector associated with the input signal with incident angle φ.

The transmitted spectrum is thus the combination of the transmitted signals defined by Eq. (3), that is

$$T = \frac{(t_x E_{i,x})^2 + (t_y E_{i,y})^2}{(E_{i,x})^2 + (E_{i,y})^2} = T_x(\cos\varphi)^2 + T_y(\sin\varphi)^2 \tag{4}$$

In Eq. (4), $t_{x(y)}$ denotes the transmission coefficient of the FBG corresponding to the $x(y)$ mode which can be derived from the modified transfer matrix method [15,22]. According to this method, the grating is divided into m uniform subgratings and the load applied on each subgrating can be treated as uniform. Based on the transfer matrix method, a 2×2 matrix is identified for each subgrating, and then the product of all these result in a single 2×2 matrix that describes the whole grating.

PDL is defined as the maximum change in the transmitted power when the input state of polarization is varied over all polarization states:

$$\text{PDL} = 10\log_{10}\left(|t_{\max}|^2 / |t_{\min}|^2\right) \tag{5}$$

where $|t_{\max}|^2$ 2 and $|t_{\min}|^2$ denote the maximum and minimum power transmitted through the component. In the case of FBG, the final expression of PDL for transmission is:

$$\text{PDL} = 10|\log_{10}(T_x/T_y)| \tag{6}$$

3. Numerical simulation and discussion for the secondary peak

In our simulations, the major parameters for all the simulations in this section are as follows: the central wavelength of the FBG without perturbation is 1546.15 nm, the FBG length L is 2 cm, average effective refractive index $n_0 = 1.445$. The incident angle will affect the amplitude spectrum while has no effect on PDL