Optical Fiber Technology 25 (2015) 15–19

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Regular Articles

Spectral response of polarization properties of fiber Bragg grating under local pressure

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ARTICLE INFO

Article history:
Received 6 September 2014
Revised 3 February 2015
Available online 15 July 2015

Keywords:
Fiber Bragg grating sensor
Local pressure
Polarization properties

ABSTRACT

A study of the spectral characterization of polarization properties of locally pressed fiber Bragg grating (FBG) is presented. The evolutions of the first Stokes (s_1) parameter of a FBG as function of the incident angle, the load magnitude, the loaded position and the loaded length of the grating are investigated. The numerical simulation based on the modified transfer matrix method is used to calculate the s_1 response and the state of polarization (SOP) of the FBG. The theoretical analysis and numerical simulation demonstrate that the evolutions of polarization dependent parameters contain the information about the transverse load and have potential applications for distributed diametric load sensor.

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. Wagreich et al. [8] studied the effect of transverse load on FBG fabricated in low birefringent fiber. The result showed that in the reflected spectrum evolution, the peaks cannot be distinguished until ~40 N of load was applied, since they overlap. However, it will lead to significant polarization parameters such as polarization dependent loss (PDL), differential group delay (DGD) and the first Stokes parameters (s_1) values within the grating, which can provide more effective information and therefore lead to the potential development of new types of FBG-based optical sensors [9,10]. We have presented a new method for real-time transverse force sensor based on the measurement of the polarization properties of a uniform fiber Bragg grating (FBG) written into standard single mode fiber [11].

However, to the best of our knowledge, no work has been reported concerning the s_1 parameters and SOP of locally pressed FBG in the literature up to now. Since the FBG is always under local transverse load in some practical applications, establishing the polarization response of the FBG under local pressure is thus beneficial in distributed FBG transverse load sensing, with the aim of developing a sensor that tracks the polarization variation as a function of the applied local load [12]. And it will helpful in getting accurate information about the transverse stress in some multi-dimensional sensor application such as inline health monitoring and damage detection of smart structure. Therefore the polarization characterization of locally pressed FBG needs additional investigation.

In this paper, the relationship of local transverse load to FBG's polarization properties especially for s_1 response are completely analyzed and presented. The wavelength dependency of s_1 evolution on the local transverse load is then numerically simulated by utilizing a modified transfer matrix method. Through numerical simulations, it is shown that the s_1 curves can be strongly affected by the incident angle, the load magnitude, the load position and the loaded length of the grating.

2. Theoretical model

A transverse and uniform distributed forces applied on FBG induces deformations of the dielectric waveguide and refractive

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http://dx.doi.org/10.1016/j.yofte.2015.07.003
1068-5200/

index changes and by consequence a birefringence. 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 To simulate a locally pressed FBG with this formalism, we consider the affected length l as a grating where the changes in refractive index are translated into a shift in the Bragg wavelength.

The relationship between stress and the induced changes in the effective refractive index is given by [13] as,

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

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

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, υ = 0.17, p_{11} = 0.121, and p_{12} = 0.270), and σ_x and σ_y are the stress components in the grating in the x, y principal directions, respectively. When the stress region is longer than the diameter of the fiber, the stresses in the axial direction σ_z will be canceled, leaving only σ_x ψ and σ_y [14]. For a given compressive force, these stresses are expressed as [15]

$$\sigma_x = \frac{2F}{\pi Dl}, \quad \sigma_y = -\frac{6F}{\pi Dl}, \quad \sigma_z = 0 \tag{2}$$

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

The refractive index in the x and y-directions is then given by $n_{eff,x} = n_{eff} + (\Delta n_{eff})_x$ ψ and $n_{eff,y} = n_{eff} + (\Delta n_{eff})_y$, with birefringence

$$\Delta n = (\Delta n_{eff})_x - (\Delta n_{eff})_y \tag{3}$$

Due to Δn, 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,

$$\begin{bmatrix} E_{o,x} \\ E_{o,y} \end{bmatrix} = \begin{bmatrix} t_x & 0 \\ 0 & t_y \end{bmatrix} \begin{bmatrix} E_{i,x} \\ E_{i,y} \end{bmatrix} = \begin{bmatrix} t_x E_{i,x} \\ t_y E_{i,y} \end{bmatrix} \tag{4}$$

$(E_{ix}, E_{iy})^T$ is the Jones vector associated with the input signal and it is given by,

$$\begin{bmatrix} E_{i,x} \\ E_{i,y} \end{bmatrix} = \begin{bmatrix} \cos\varphi \\ \sin\varphi \end{bmatrix} \tag{5}$$

where φ is the incident angle of the input light.

The transmitted spectrum is thus the combination of the transmitted signals defined by Eq. (4), that is

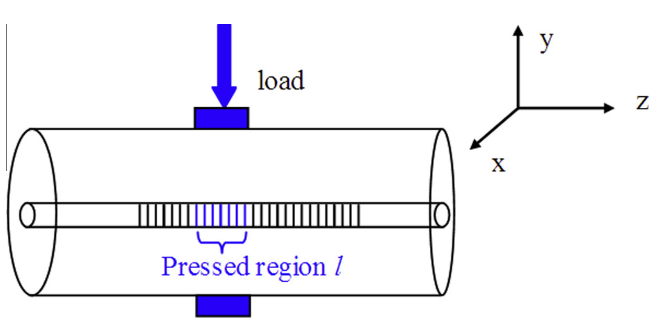

Fig. 1. Schematic diagram of a FBG subjected to local transverse load.

$$T = \frac{(t_x E_{i,x})^2 + (t_y E_{i,y})^2}{(E_{i,x})^2 + (E_{i,y})^2} = T_x(\cos\varphi)^2 + T_y(\sin\varphi)^2 \tag{6}$$

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 [16,17]. 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.

The Stokes parameters represent the state of polarization. They can be deduced from the Jones vector by means of the follows equations:

$$S_0 = |E_{ox}|^2 + |E_{oy}|^2, \quad S_1 = |E_{ox}|^2 - |E_{oy}|^2,$$
$$S_2 = 2\mathrm{Re}[E_{ox}^* E_{oy}], \quad S_3 = 2\mathrm{Im}[E_{ox}^* E_{oy}]$$

The normalized Stokes parameters (s_1, s_2 and s_3) can then be computed using the relationship:

$$s_i = S_i/S_0 \quad (i = 1, 2, 3) \tag{8}$$

For s_1,

$$s_1 = \frac{S_1}{S_0} = \frac{|E_{ox}|^2 - |E_{oy}|^2}{|E_{ox}|^2 + |E_{oy}|^2} = \frac{|t_x\cos\varphi|^2 - |t_y\sin\varphi|^2}{|t_x\cos\varphi|^2 + |t_y\sin\varphi|^2}$$
$$= \frac{T_x|\cos\varphi|^2 - T_y|\sin\varphi|^2}{T_y|\cos\varphi|^2 + T_y|\sin\varphi|^2}$$

So the relationship between transverse load and the normalized Stokes parameters are founded using Eqs. (1)-(8)

3. Numerical simulation and discussion

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, n_0 = 1.445, the amplitude of refractive index modulation is 2.5×10^{-5}. A numerical simulation based on the modified transfer matrix method described in Section 2 was adopted to simulate the s_1 spectrum of a FBG under the local transverse load. The simulated results are then analyzed to determine the relationship between the evolution of the s_1 response and the load magnitude, the loaded position and the loaded length of the grating.

3.1. Effect of incident angle

As we all known, When 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, the effect of which is equivalent to creating a phase shift and thus introduce a spectral hole within the bandwidth of the FBG [16]. When the applied strain is not isotropic, the effects in the spectral response on the grating will depend on the light polarization. Firstly, the effect of the incident angle on the transmission spectrum and s_1 evolution of the FBG is investigated using the above mentioned method. We consider the case when the center of the FBG is loaded transversely in a very small region (0.2 mm) and the load magnitude is assumed to be 5 N. Fig. 1(a) and (b) shows the simulated transmission and s_1 spectra for several incident angles.

We can see that the incident angle has important effect on the transmission and s_1 response of the FBG. As we all known, when the direction of the transverse load is assumed as y axis, the changes of refractive index of x axis will be larger than that of y axis. So when the light is partially polarized, the more the weight