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Numerical Study of Fiber Bragg Grating Sensor: Longitudinal and Transverse Detection of Temperature and Strain

K. Khelil, H. Ammar, K. Saouchi

Abstract**—**Fiber Bragg Grating (FBG) structure is an periodically modulated optical fiber. It acts as a selective filter of wavelength whose reflected peak is called Bragg wavelength and it depends on the period of the fiber and the refractive index. The simulation of FBG is based on solving the Coupled Mode Theory equation by using the Transfer Matrix Method which is carried out using MATLAB. It is found that spectral reflectivity is shifted when the change of temperature and strain is uniform. Under non-uniform temperature or strain perturbation, the spectrum is both shifted and destroyed. In case of transverse loading, reflectivity spectrum is split into two peaks, the first is specific to X axis, and the second belongs to Y axis. FBGs are used in civil engineering to detect perturbations applied to buildings.

Keywords**—**Bragg wavelength, coupled mode theory, optical fiber, temperature measurement.

I. Introduction

In past forty years, revolution is brought out in information technology due to developments in optoelectronics and telecommunication industries. In fiber optic sensors, information is conveyed by change either in phase, polarization, frequency, wavelength, intensity or combination of above properties of optical fiber.

Currently, FBGs [1]-[3] are applied as optical filters, couplers, reflectors, dispersion comparators, etc. This wave guide has many applications in telecommunication technology, sensing and optical ranging. It is use as sensor for measuring several magnitudes such as strain, temperature and pressure [4]-[6], [15]-[29] is progressing since about 20 years [7], when the photosensitivity of germanium-doped silica fiber has been discovered by Hill et al. in 1978 [8], [9]. The fabrication of FBG is done by inscribing a periodic variation of refractive index of its core using an intense ultraviolet (UV) source such as a UV laser.

Used in the field of sensing, FBG has many advantages, such as good durability, anti-electromagnetic interference, single-ended input, small size, quasi-distribution measurements, anti-moisture, and being independent of intensity [4], [8].

The concept of FBG is based on the theory of Bragg reflection; FBGs usually reflect light in a short range of wavelength and transmit remaining wavelengths. When light propagates through the FBG, the total reflection takes place at Bragg wavelength and the remaining wavelengths are not affected by the Bragg grating except a few side lobes existing in reflection spectrum. [2]

Khelil Khadidja is with the Badji Mokhtar University, Algeria (e-mail: khadidjaoptics@gmail.com).

FBGs exhibit well-behaved wavelength responses to temperature and strain, its response is then coded in wavelength [1]-[3]. In order to show that the FBG is compatible as a sensor, we characterized the central wavelength shift and shape of the FBG's reflected spectrum under temperature change and applied strain.

Many researchers have analyzed the temperature and strain sensing characteristics of FBG. However, those analyses are all for a uniform temperature and strain field. Analyses of spectra of non-uniform temperature strain fields are very few [10], [11].

In this paper, we show and discuss not only uniform fields of temperature, but also non-uniform change of temperature and strain. The transverse load of temperature and strain is discussed.

II. Equation

The principal of FBG is to reflect a precise wavelength when a light passes through it and transmit remaining wavelengths. The reflected wavelength depends on the grating period and refractive index, therefore it is called Bragg wavelength. According to Bragg law, inside of the sensor, there are two propagating lengths, the transmitted, and the reflected. FBG is then a weakly coupled waveguide structure, so it can be studied by CMT [2], [6], [12]-[14]; in this approximation, backward and forward propagation modes are expressed as:

$$E(x,y,z,t)= (A(z) \exp(i\beta z)+ B(z) \exp(-i\beta z))e(x,y)\exp(it) \quad (1)$$

A(z); B(z) gradually varying amplitudes of j-th mode backward and forward respectively; e(x,y) is across field distribution; β propagating constant; ω angular frequency; A(z) and B(z) mode's evolution along the grating length is obtained by CMT and given by:

$$\frac{dS}{dz}=i\Omega R(z)+ikS(z) \quad (2)$$

$$\frac{dR}{dz}= -i\Omega R(z)-ikS(z) \quad (3)$$

S, R are forward and backward propagating waves respectively; and are related by CMT as equations and S (z); R

(z) are amplitudes of forward and backward propagating mode respectively.

$$S(z) = A(z)\exp(i\delta z + \varphi/2) \quad (4)$$

$$R(z) = B(z)\exp(i\delta z - \varphi/2) \quad (5)$$

where:
$\Omega=\delta+\sigma-\frac{d\varphi}{2dz}$; $K=\frac{\pi}{\lambda}\nu\Delta n_{eff}$; $\sigma=\frac{2\pi}{\lambda}\Delta n_{eff}$; $\delta=2\pi n_{eff}(\frac{1}{\lambda}-\frac{1}{\lambda B})$

Parameters above are defined as:

- Ω "dc" coupling self-coefficient
- K "AC" coupling coefficient
- σ "DC" coupling coefficient
- δ detuning

When FBG is uniform: $\frac{d\varphi}{2dz}=0$. In uniform loading, the Transfer Matrix satisfies the following relation:

$$\begin{bmatrix} S_0 \\ R_0 \end{bmatrix} = T\begin{bmatrix} S_N \\ R_N \end{bmatrix} \quad (6)$$

If the loading is non-uniform, the Transfer Matrix of each individual segment is assumed as Ti

$$\begin{bmatrix} S_0 \\ R_0 \end{bmatrix} = T\begin{bmatrix} S_N \\ R_N \end{bmatrix} = \prod_{i=1}^{N} Ti\begin{bmatrix} S_N \\ R_N \end{bmatrix} \quad (7)$$

Total Matrix is then:

$$T = T_N . T_{N-1} \ldots\ldots\ldots T_2 . T_1$$

Elements of individual section's matrix are:

$$\begin{bmatrix} S_i \\ R_i \end{bmatrix} = T_i\begin{bmatrix} S_{i+1} \\ R_{i+1} \end{bmatrix} = \begin{bmatrix} T_{11}^i & T_{12}^i \\ T_{21}^i & T_{22}^i \end{bmatrix}\begin{bmatrix} S_{i+1} \\ R_{i+1} \end{bmatrix} \quad (8)$$

where:

$$T_{11}^i = \cosh(\gamma_B\, dz_i) + i\frac{\Omega}{\gamma_B}\sinh(\gamma_B\, dz_i) \quad (9)$$

$$T_{22}^i = \cosh(\gamma_B\, dz_i) - i\frac{\Omega}{\gamma_B}\sinh(\gamma_B\, dz_i) \quad (10)$$

$$T_{12}^i = i\frac{k}{\gamma_B}\sinh(\gamma_B\, dz_i) \quad (11)$$

$$T_{21}^i = -\,i\frac{k}{\gamma_B}\sinh(\gamma_B\, dz_i) \quad (12)$$

$$\gamma_B = \sqrt{k^2+\Omega^2} \quad (13)$$

Bragg law is described as:

$$\lambda_B = 2n_{eff}\,\Lambda \quad (14)$$

As a strain sensor, the shift in Bragg wavelength is related to strain as:

$$\Delta\lambda_B = \lambda_B\,(1-p_e)\xi \quad (15)$$

$$p_e = \frac{n^2}{2}(p_{12} - \nu(p_{11}+p_{11})) \quad (16)$$

p_{11}, p_{12} strain tensors, ν Poisson's ratio, p_e strain optic coefficient, n refractive index. The shifted Bragg wavelength is then:

$$\lambda_B' = \lambda_B + \Delta\lambda_B \quad (17)$$

$$\Delta\lambda_B = \lambda_B\,(\alpha+\xi)\,\Delta T \quad (18)$$

where: $\alpha = \frac{1}{n_{eff}}\frac{\Delta n_{eff}}{\Delta T}$; $\xi = \frac{1}{\Lambda}\frac{\Delta\Lambda}{\Delta T}$; ξ is the thermal expansion coefficient and α is the thermo-optic coefficient. The shifted Bragg wavelength is then:

$$\lambda_B' = \lambda_B + \Delta\lambda_B \quad (19)$$

FBG sensor can have a double sensitivity, to strain and temperature at the same time, the shift is then:

$$\Delta\lambda = k_t\Delta T + k_e\Delta\xi + \Delta k_t \Delta k_e \Delta\xi \quad (20)$$

III. Results

A. Reflectivity Spectrum

Fig. 1 shows the reflectivity spectrum of the FBG, the reflected wave is called the Bragg wave and its wavelength depends on the parameters of the FBG. Other wavelengths of the incident wave are transmitted.

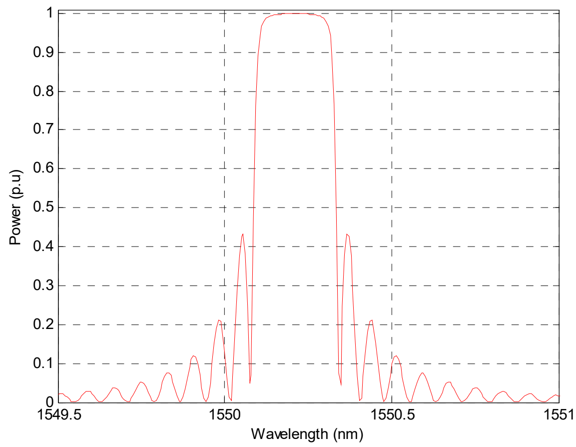

Fig. 1 Reflectivity spectrum

B. Spectrum Shift under Uniform Temperature

Fig. 2 (a) shows the different temperature values applied on the FBG. The temperature applied is constant along the FBG. The response is illustrated in Fig. 2 (b). The result is a shift in wavelength in a consistent manner with each temperature value, without changing the shape of the spectrum.

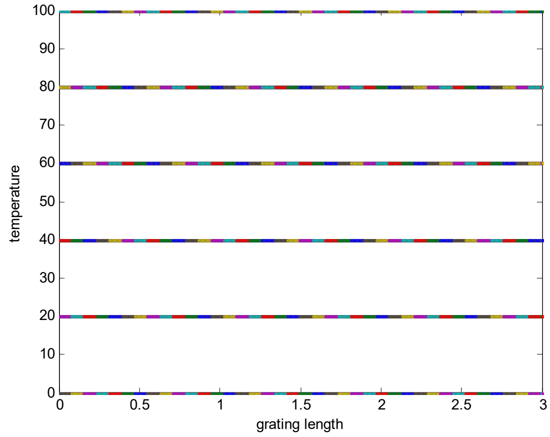

Fig. 2 (a) Constant values of temperature applied on FBG

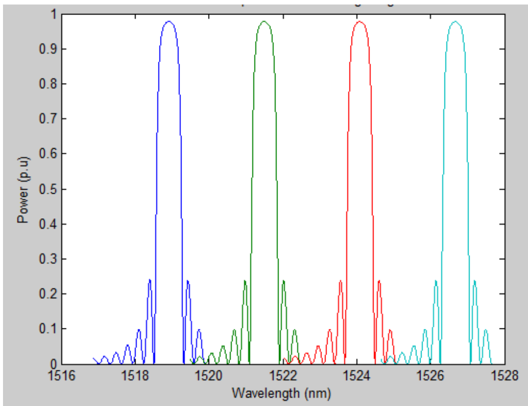

Fig. 2 (b) Shift of reflectivity spectrum under uniform temperature

C. Spectrum Shift under Uniform Strain

Fig. 3 (a) shows the different strain values applied on the FBG. The strain applied is constant along the FBG. The response is illustrated in Fig. 3 (b). The result is a shift in wavelength in a consistent manner with each strain value, without changing the shape of the spectrum.

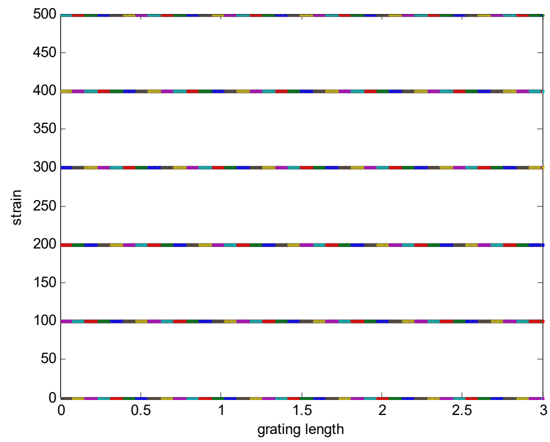

Fig. 3 (a) Constant values of strain applied on FBG

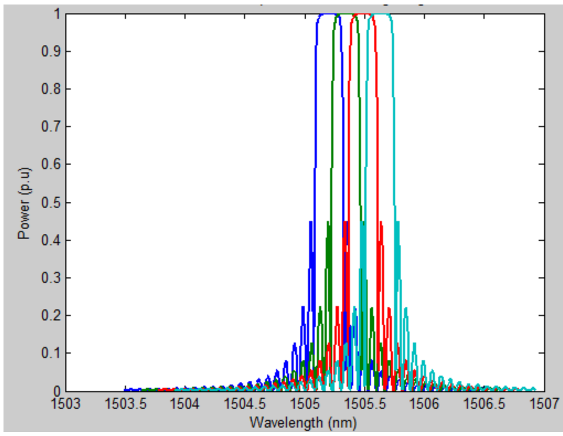

Fig. 3 (b) Shift of reflectivity spectrum under uniform strain

D. Spectrum Shift under Non-Uniform Temperature

Fig. 4 (a) shows a non-uniform temperature applied on FBG. The simulation is done by division of the FBG length to small segments. Then we apply on each segment a constant value of temperature, and then we multiply all matrices. The response is illustrated in Fig. 4 (b). The result is a distortion of the reflectivity spectrum and a shift in wavelength.

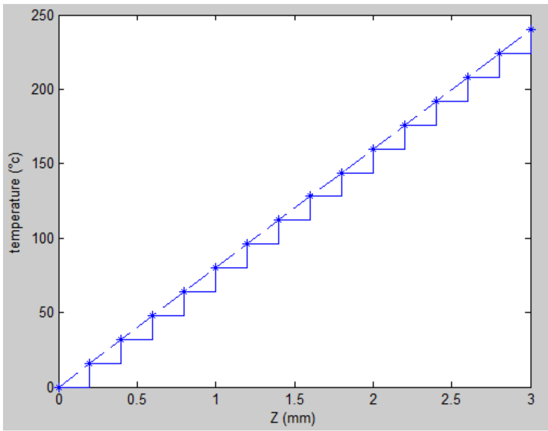

Fig. 4 (a) Non-uniform temperature applied on FBG

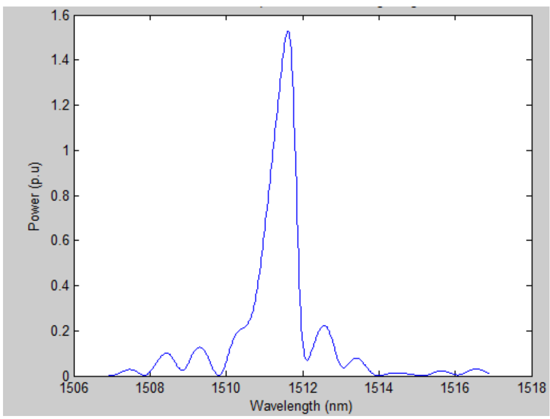

Fig. 4 (b) Shift of reflectivity spectrum under non-uniform temperature

E. Spectrum Shift under Non-Uniform Strain

Fig. 5 (a) shows a non-uniform temperature applied on FBG. The simulation is done by division of the FBG length to small segments, we appropriate to each segment a constant value of temperature, and then we multiply all matrices. The response is illustrated in Fig. 5 (b). The result is a distortion of the reflectivity spectrum and a shift in wavelength.

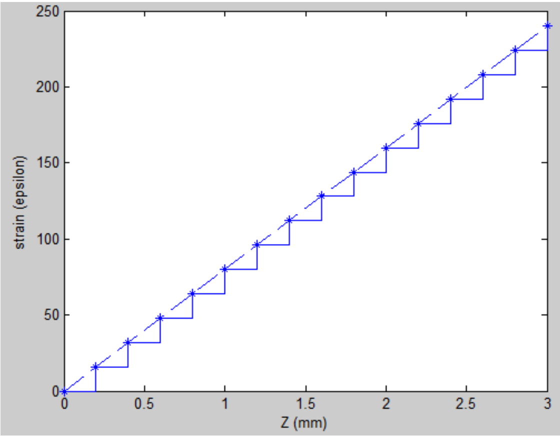

Fig. 5 (a) Non-uniform strain applied on FBG

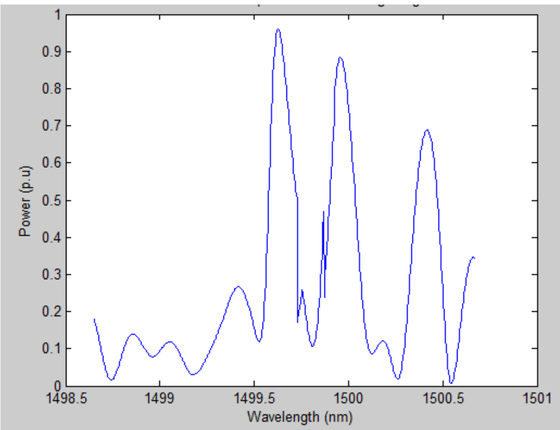

Fig. 5 (b)Shift of reflectivity spectrum under non-uniform strain

F. Spectrum Splitting under Biaxial Loading

When the FBG is inscribed under a birefringent fiber or if the strain is different on each axis, the reflectivity spectrum splits into two peaks instead of one.

IV. Discussion

Simulation results of reflectivity show that perturbation of temperature brings changes on the response spectrum. Main changes are in side lobes, central peak's intensity and shape, and a shift in Bragg wavelength when the perturbation is non-uniform (Figs. 4, 5). When the perturbation is uniform only a shift in wavelength appears (Figs. 2, 3). If the FBG detects transverse change in the temperature or the strain, the peak is then divided in two peaks (Fig. 6).

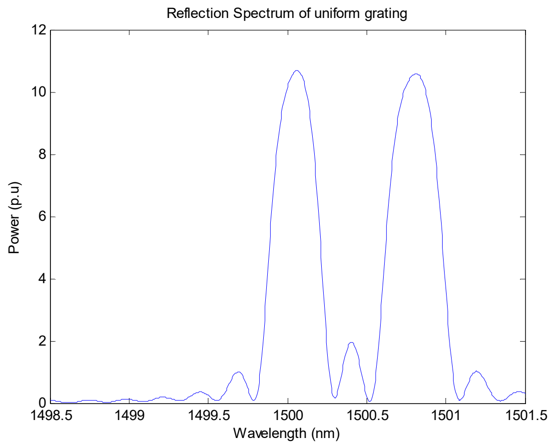

Fig. 6 Biaxial measurement of FBG

V. Conclusion

The accurate sensitivity to temperature and strain qualifies the FBG to be a temperature and strain sensor. As perspective, researches are ongoing on reverse-calculation, a temperature or strain sensor that gives not only a response, but also the value or the function of the temperature and strain. Many works have proposed the genetic algorithm for that [31], [32], when we should put the population, and using algorithm tools, the temperature and strain are calculated.

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