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Parametric Analysis by Simulation of Bragg Gratings and Their Application as a Sensor

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In this research paper, the impact of an opto-geometric fiber Bragg grating (FBG) is theoretically studied through simulation using the Rsoft Photonics CAD software's Grating Mod module, which is based on the coupled mode theory. Furthermore, the FBG is an optical component that plays a growing role in instrumentation. Moreover, its structure is based on a modification of the refractive index of the fiber core. Besides, the influence of several parameters, such as grating period, its length, its index difference, was presented and examined. The simulation results obtained show that the Bragg wavelength of the network shifts and changes its value following a change in one of its parameters. This means that the sensitivity of the FBG is considerable. However, because of the insensitivity to electromagnetic disturbances and the small size, which is suitable for that of the arteries, the adjustment of the FBG reflection characteristics under the action of a quantity is used to create miniaturized and sensitive sensors which are useful in medicine.

Keywords: Fiber Bragg grating (FBG), Grating mod module, Refractive index, Bragg wavelength.

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1. INTRODUCTION

With the continuous development of broadband communication systems and wavelength multiplexing technology, the creation of new optical fiber components and wavelength-selective devices has become increasingly significant [1-3]. The use of Bragg gratings solves some problems related to fiber optic communication systems [4-6]. Besides, this component is widely used in the field of sensors; this is mainly due to its multifunctional characteristics.

Fiber optic-based sensors now offer the same functions as traditional ones: measurement, control, alarm detection and monitoring, while presenting specific functions related to optical fibers such as small footprint, light weight, high bandwidth, low attenuation, the absence of electromagnetic interference, the possibility of using in severe environments, and the possibility of multiplexing numerous sensors [7-10]. In fact, optical sensors have excellent measurement performance in terms of sensitivity, time response and range of use [11-13].

Among the optical sensors, there is a fiber Bragg grating (FBG), which has multifunctional characteristics to be used as a sensor. Therefore, by making a change in a section of optical fiber to affect the refractive index of its core, this allows the selectivity of several particular wavelengths, which may be sensitive to changes in temperature or stress [14-16].

The applications of Bragg gratings are generally based on the characteristics of the reflected wave that is why the characterization of the grating takes on great significance, as well as its sizing. Therefore, this work objective is the simulation and characterization of a multifunctional FBG in a field of sensors. To conduct various simulations of the studied spectral response of Bragg gratings, the Grating Mod module of the commercial software Rsoft was used. It is optimized to perform a fast and reliable calculation of the spectral response of a Bragg grating that is defined in a relatively simple way. Furthermore, we studied the influence of opto-geometrical parameters on the spectral response of FBG.

The structure of the document is as follows. Section 1 presents a succinct overview of fiber optic sensors and FBGs. The model of the FBG sensor and the software design process are both covered in Section 2. The simulation results and discussion are reported in Section 3 along with a study of the impact of various factors on the spectral response of FBG. Concluding remarks are included in Section 4.

2. DESIGN AND THEORETICAL ANALYSIS

In this section, we first present the design of the FBG sensor and then describe the methodology that was used in the software tool for its design.

2.1 Design and Structure of the FBG sensor

The simulated FBG sensor model is shown in Fig. 1. The FBG is a microscopic structure constructed in the core of an optical fiber that consists of a longitudinal and periodic modulation of the fiber refractive index.

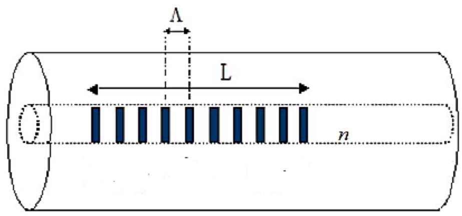

Fig. 1 – Schematized model of the FBG sensor

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FBGs are produced by exposing a photosensitive fiber to a UV light intensity pattern. The resulting grating, in its simplest form, selectively reflects light guided by the optical fiber at the Bragg wavelength $\lambda_B = 2n\Lambda$, where n and Λ are the respective values of the effective refractive index of the fiber and the pitch of the grating within the fiber [9]. The principle behind FBG sensors is that the Bragg wavelength shifts as the refractive index and grating pitch change.

With the assistance of reducing software modules like the GratingMOD, an optical FBG sensor model is simulated, and the modeled sensor is assessed for the grating efficiency for a range of factors, such as pitch, length, and index variation.

Using the Rsoft software's Grating Mode module, which is based on the concept of coupled modes [17], the simulation is carried out by integrating the FBG model from Fig. 1 into the software.

2.2 Coupled Mode Theory

The coupled mode theory developed by Haus [18-20] is used in our model.

We consider a system based on an input port, an output port, and a resonator. The coupled mode scheme is depicted in Fig. 2.

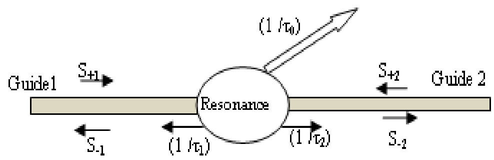

Fig. 2 – Sketch of the coupled mode model for a resonant cavity

The amplitude of the electric field of the mode inside the cavity is noted a. The amplitudes of the incoming waves (respectively, outgoing) in the system are denoted $S_{+i}(S_{-i})$, where $i = 1.2$. When the incident wave propagates in the guide (1), it can partially enter the resonator and then return to the guide (2) or be reflected in the opposite direction.

The intrinsic losses are defined by τ_0, which is the duration of time that photons stay in the cavity before escaping. The durations τ_1 and τ_2 of the photons in the cavity before they escape to the two waveguides 1 and 2, respectively, are used to describe the strength of the coupling between the guides and the resonator. The squared magnitude $|a|^2$ corresponds to the field energy.

The amplitude of the electric field can be written as follows:

$$a(t)\,\alpha\; e^{j\omega_0 t} e^{-\frac{t}{\tau_0}} e^{-\frac{t}{\tau_1}} e^{-\frac{t}{\tau_2}} . \quad (2.1)$$

The power inside the cavity increases as a function of that of the incident wave S_{+i} by the coupling coefficient: $\kappa_1 = \sqrt{\frac{2}{\tau_1}} S_{+1}$.

The temporal evolution of the resonator mode amplitude is then written as [18]:

$$\frac{da}{dt} = \left(j\omega_0 - \frac{1}{\tau_0} - \frac{1}{\tau_1} - \frac{1}{\tau_2} \right) a(t) + \sqrt{\frac{2}{\tau_1}} S_{+1} + \sqrt{\frac{2}{\tau_2}} S_{+2} , \quad (2.2)$$

Where ω_0 is the resonant frequency.

For a symmetric system $\tau_1 = \tau_2$, so we can express:

$$a(\omega) = \frac{\sqrt{\frac{2}{\tau_1}} S_{+1} + \sqrt{\frac{2}{\tau_2}} S_{+2}}{\left(j(\omega - \omega_0) + \frac{1}{\tau_0} + \frac{2}{\tau_2} \right)} . \quad (2.3)$$

There is no incoming wave in port 2, $S_{+2} = 0$, the output power S_{-2} comes from the resonant cavity, so we can write [18]:

$$|S_{-2}| = \frac{2}{\tau_2} |a|^2 . \quad (2.4)$$

The combination of equations (2.1)-(2.4) makes it possible to calculate the expressions for transmission and reflection in the guide:

$$T = \left| \frac{S_{-2}}{S_{+1}} \right|^2 = \left| \frac{\frac{2}{\tau_2}}{j(\omega - \omega_0) + \frac{2}{\tau_2} + \frac{1}{\tau_0}} \right|^2 ,$$

$$R = \left| \frac{S_{-1}}{S_{+1}} \right|^2 = \left| \frac{-j(\omega - \omega_0) + \frac{1}{\tau_2} - \frac{1}{\tau_2} - \frac{1}{\tau_0}}{j(\omega - \omega_0) + \frac{2}{\tau_2} + \frac{1}{\tau_0}} \right|^2 .$$

3. Simulation Analysis of the Influence of Characteristic Parameters on the Spectral Response of FBG

In our work, we modify each time the FBG parameter with a constant step, and then we notice the obtained simulation results in a table. After that we represent them in the form of a graphic curve, finally we analyze the results and use FBG as a sensor.

3.1 The Impact of the Period

We study the influence of the period on the spectral response in a constant pitch FBG structure in order to study the effect of this parameter on the spectral response of the FBG. In this simulation, the geometric parameters of the FBG structure previously presented will be used. For several values of the period (Λ = 0.3 μm up to 0.6 μm), we measured each time the reflection coefficient and its corresponding wavelength.

These results were used in graphics software 'Microcal Origin 6.0', which allowed us to plot the variation of the wavelength as a function of the grating pitch. Fig. 3 shows the variation of the Bragg wavelength with the pitch of the grating; we notice that the wavelength λ varies linearly and proportionally with the grating pitch Λ.

Fig. 4 shows the spectral response of the FBG obtained for four grating pitch values (Λ = 0.5, 0.52, 0.54 and 0.56 μm).

We notice that the reflection spectrum is offset from the reference reflection spectrum. The Bragg wavelength changed from 1.453 to 1.510 μm when the pitch changed from 0.5 to 0.52 μm, the same for Λ = 0.54 μm and Λ = 0.56 μm. The variation of the grating pitch is responsible for the change in the Bragg wavelength.

Table 1 – Values of the reflection coefficient and wavelength of the FBG as a function of the grating pitch Λ

Λ (μm)	Reflection coefficient	λ (μm)
0.3	0.9857	0.8730
0.32	0.9836	0.9311
0.34	0.9816	0.9891
0.36	0.9795	1.047
0.38	0.9775	1.105
0.4	0.9734	1.163
0.42	0.9693	1.221
0.44	0.9631	1.279
0.46	0.957	1.337
0.48	0.9488	1.395
0.5	0.9406	1.453
0.52	0.9303	1.510
0.54	0.918	1.568
0.56	0.9037	1.626
0.58	0.8871	1.684
0.6	0.8668	1.742

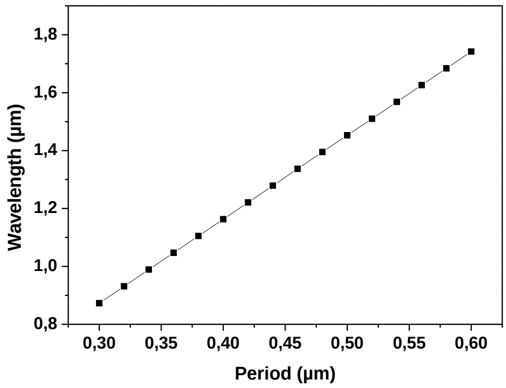

Fig. 3 – Wavelength variation as a function of grating pitch

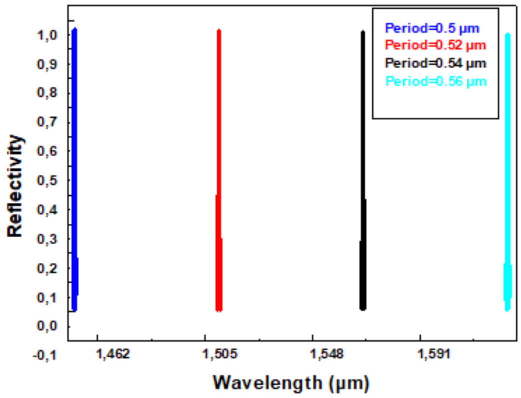

Fig. 4 – Spectral response of the FBG obtained for four grating pitch values (Λ = 0.5, 0.52, 0.54 and 0.56 μm)

The analysis of all these results shows that the variation in the wavelength can be attributed to a change in temperature, thus the FBG is sensitive to the thermal effect; therefore, it can be used as a temperature sensor. The FBG can be applied as a displacement sensor, as it explains the displacement in the position of the spectrum when we change the pitch. The FBG has characteristics to be used as a sensor (linearity, sensitivity).

3.2 The Effect of Index Difference Variation

In this simulation, the geometric parameters of the FBG structure presented before will be used. For several values of the index variation ($\Delta = 0.4 \cdot 10^{-2}$ up to $\Delta = 2.2 \cdot 10^{-2}$), we measured each time the reflection coefficient and the wavelength.

Fig. 5 shows the variation of the Bragg wavelength with the variation of index difference Δ.

Table 2 – Values of the reflection coefficient and wavelength as a function of the index difference variation

Δn	R	wavelength (μm)
0.004	0.6527	1.45
0.006	0.8495	1.451
0.008	0.9208	1.453
0.01	0.9472	1.454
0.012	0.9604	1.455
0.014	0.9734	1.457
0.016	0.9736	1.459
0.018	0.9769	1.460
0.02	0.9835	1.462
0.022	0.9835	1.464

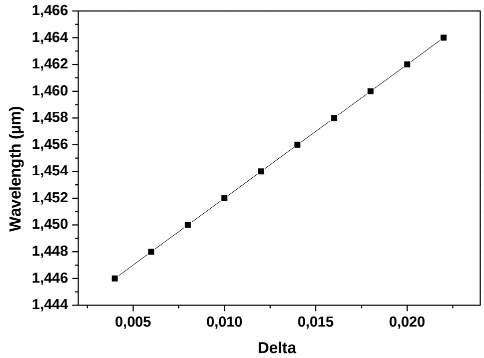

Fig. 5 – Wavelength variation as a function of index difference Delta

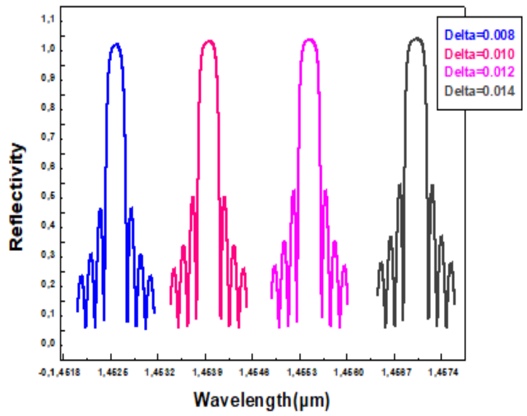

Fig. 6 – FBG spectral response obtained for four index difference values (Δ = 0.008, 0.01, 0.012, and 0.014)

We notice that the wavelength λ varies linearly and proportionally with the index difference Δ noted 'Delta'.

In Fig. 6, the spectral response of the FBG obtained for four index difference values (Δ = 0.008, 0.01, 0.012, and 0.014) is respectively reported.

The reflection spectrum is translated successively with respect to the reference reflection spectrum (Fig. 6).

The Bragg wavelength changed from 1.453 to 1.454 µm, when the index variation changed from 0.008 to 0.014. The variation of the index difference is responsible for the change in the Bragg wavelength.

The analysis of all these results shows that the sensor works on the principle of tracking the Bragg wavelength, where the latter is expressed as a function of the effective index and network period. These two physical quantities themselves are dependent on external quantities of thermal, mechanical, electromagnetic and even chemical and hygrometric origin. This confirms the application of FBG in instrumentation as a promising optical sensor.

3.3 The Effect of Grating Length

Fig. 7 shows the effect of grating length (*L*) on the spectral response of FBG.

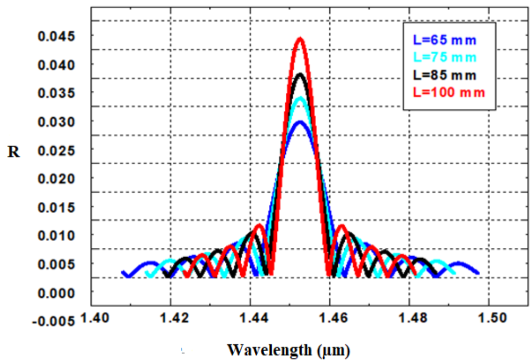

Fig. 7 – Effect of grating length on spectral response of FBG

It is observed that there is an increase in the FBG spectrum peak when the grating length changes from $L = 65$ mm to $L = 100$ mm.

We can explain the spectrum deformation by the stress applied to the FBG, thus this optical component can be used as a seismic sensor, a vibration sensor or a force sensor.

4. CONCLUSIONS

The presented article is devoted to the simulation of a fiber Bragg grating called 'FBG'. The latter finds a very significant place among new optical sensors. The development of a design equivalent to a real structure using Rsoft simulation software allows to study the influence of various key parameters. We studied the influence of geometric and physical parameters (grating pitch, index variation, grating length, as well as modulation depth) on the spectral response of FBG. We were able to evaluate the respective influence of its different parameters on the operation and dynamics of the output signal in order to apply it as a sensor.

The simulation results obtained show that the Bragg wavelength of the grating shifts and changes in value, following a change in one of its parameters. However, the sensitivity of FBG is considerable, as this variation in wavelength can be attributed to a change in temperature, stress, or other disturbance. Therefore, the FBG has multifunctional characteristics as a promising optical sensor.

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Параметричний аналіз шляхом моделювання брегівських ґраток та їх застосування як датчика

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У статті вплив оптико-геометричної волоконної брегівської ґратки (FBG) теоретично вивчається шляхом моделювання за допомогою модуля Grating Mod програмного забезпечення Rsoft Photonics CAD, який базується на теорії зв'язаних мод. FBG є оптичним компонентом, який відіграє все більшу роль у приладобудуванні. Крім того, його структура заснована на модифікації показника заломлення серцевини волокна. Було представлено та досліджено вплив кількох параметрів, таких як період ґратки, її довжина та індекс модуляції. Отримані результати моделювання показують, що Брегівська довжина хвилі мережі зміщується та змінює своє значення після зміни одного з її параметрів. Це означає, що чутливість FBG є значною. Однак через нечутливість до електромагнітних перешкод і малого розміру, регулювання характеристик відбиття FBG використовується для створення мініатюрних і чутливих датчиків, які є корисними в медицині.

Ключові слова: Волоконна брегівська ґратка (FBG), Модуль Grating Mod, Показник заломлення, Брегівська довжина хвилі.