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Bandwidth Characteristics of FBG Sensors for Oil and Gas Applications

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Abstract In this paper we perform a numerical analysis of fiber Bragg grating (FBG) bandwidth characteristics for oil and gas sensing applications. It is shown that the grating length (L_g) and the change in the refractive index profile (δ_n) represent a key parameters in contributing to high FBG sensor performance. The analysis based on solving coupled mode equations were carried out using MATHCAD software. Results show that the changes in the L_g and δn affect the FBG bandwidth significantly at a time when demand for bandwidth is growing in oil and gas sensing applications. The obtained results are very important for FBG sensor applications.

Keywords: *coupled-mode equations, fiber Bragg grating (FBG), FWHM, reflectivity, oil and gas sensing*

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1. Introduction

For many years, the oil and gas industry has depended strongly on electronic sensor devices (ESDs), where several kilo-meters into the subsurface, are used to measure a wide range of parameters such as pressure, temperature along the well, flow and vibration [1,2]. However, due to the environmental conditions as the acoustic signals resulting from seismic activities, the mechanical stress on structural components and the geological nature of the ground make these devices suffer from a large limitations such as the corrosion in the electrical parts, the increase in the error-rate, the lack of reliability, and the electromagnetic interference (EMI) effect resulting from the harsh and extreme used conditions [3]. Add to that, the use of many ESDs makes the process of the downhole sensing and monitoring is very difficult and complex.

Recently, the significant progress in the field of optical sensor technology have led to the expansion of the applicability limits of fiber Bragg grating (FBG), where it present unique features that have no match in conventional sensing techniques [4,5]. Beside the ability to measure temperatures and strain at thousands of points along a single optical fiber, it is particularly interesting for the monitoring of elongated structures such as pipelines, flow lines, oil wells and coiled tubing [6].

Fiber Bragg gratings are formed by a periodic perturbation of the core refractive index of an optical fiber formed by exposing a periodic pattern of high-intense UV light, which results in a permanent variation to the refractive index of the core of the fiber [6]. At certain conditions, the constructive interference of the reflected wavelengths results in a band rejection which is known as the Bragg wavelength and is dependent on the refractive index and the grating period, so any changes on the grating structure or physical model will cause a shift on the rejected wavelength. This makes the mentioned parameters to be useful sensed tools [6].

The FBG technology is used widely in oil and gas sensing applications due to the numerous advantages over the ESDs. FBG are intrinsically passive devices, intrinsically safe, high sensitivity, immune to EMI, perfect for high temperature range operation, small size and light weight. Add to that, their capability for multiplexing compare with other fiber configurations that allows a single optical fiber cable with tens of gratings to measure a large range of parameters in oil and gas production [7,8,9,10].

FBG are wavelength-dependent structures that can be easily adjusted by proper design [11]. One of the most important features of the FBG is the narrow bandwidth of the rejected wavelength. However, some applications in the oil and gas industry such as seismic sensing need large bandwidth [12]. In this study, using numerical analysis, the effects of grating length and fiber refractive index have investigated to achieve a large FBG bandwidth to be suitable for oil and gas industry applications.

2. Coupled Mode Theory: Basic Gratings Fiber Analysis

One of the most useful ways to analyze the light propagation in waveguides is the coupled mode theory (CMT). It depend on defining the propagate modes and solve it. Then, the obtained solutions are used in Maxwell's equations, which can be solved analytically or by a numerical methods. CMT assumes that the field can be represented by a linear superposition of the modes of the coupled structures [6]. Assuming linear combination for the ideal modes, the electric field is given by [6]

$$E(z)=\sum_k\left[A_k^+\exp(-j\beta_k z)+A_k^-\exp(j\beta_k z)\right]\mathrm{E}_k \quad (1)$$

Where A_k^+, A_k^-, β_k and E_k are the slowly varying amplitudes of kth mode traveling in the +z and –z directions, the propagation constant and the modal field of the kth mode, respectively. Using the waveguide modes properties, the coupled mode Equations can be derived as [6]

$$\frac{dA_k^+}{dz}=-j\sum_m\left\{A_m^+C_{mk}\exp\left[-j\left(\beta_m-\beta_k\right)z\right]+A_m^-k_{mk}\exp\left[j\left(\beta_m+\beta_k\right)z\right]\right\} \quad (2)$$

$$\frac{dA_k^-}{dz}=j\sum_m\left\{A_m^+C_{mk}\exp\left[-j\left(\beta_m+\beta_k\right)z\right]+A_m^-k_{mk}\exp\left[j\left(\beta_m-\beta_k\right)z\right]\right\}. \quad (3)$$

For a single mode FBG, Eqs. (2) and (3) are simplified to [6]

$$\frac{dA_k^+}{dz}=-j\hat{\sigma}A_k^+(z)-j\kappa^*A_k^-(z) \quad (4)$$

$$\frac{dA_k^-}{dz}=j\hat{\sigma}A_k^-(z)+j\kappa A_k^+(z) \quad (5)$$

Where $\hat{\sigma}$ and κ are the general dc and ac coupling coefficient, respectively. They are defined as [6]

$$\hat{\sigma}=\delta+\sigma-\frac{1}{2}\frac{d\varphi}{dz} \quad (6)$$

$$\kappa=\kappa^*=\frac{\pi}{\lambda}v\bar{\delta}n_{eff} \quad (7)$$

where $\bar{\delta}n_{eff}$ is the dc change in the effective fiber refractive index, v is the fringe visibility and $\varphi(z)$ denotes the grating chirp. The detuning δ and σ in Eq. (6) are defined as [6]

$$\delta=\beta-\frac{\pi}{\Lambda}=2\pi n\left(\frac{1}{\lambda}-\frac{1}{\lambda_B}\right) \quad (8)$$

$$\sigma=\frac{2\pi}{\lambda}\bar{\delta}n_{eff} \quad (9)$$

Where Λ, n and λ_B are the grating period, refractive index of the fiber core and the Bragg wavelength, respectively. By solving the coupled mode equations using the transfer matrix method to obtain the FBG spectral response, the analytical expression of the reflectivity for a uniform FBG is obtained as [6]

$$r=\frac{\sinh^2\left(\sqrt{\kappa^2-\hat{\sigma}L_g}\right)}{\cosh^2\left(\sqrt{\kappa^2-\hat{\sigma}L_g}\right)-\frac{\hat{\sigma}^2}{\kappa^2}} \quad (10)$$

Where L_g is the length for the grating fiber.

3. Parameters of FBG Sensing

Basically, there are three key factors that control the properties of the FBG; the fiber grating length, the grating strength and the refractive index. The main sensing parameters using FBG are the temperature, the strain and the pressure. Essentially, sensor technology is based on the varying in the Bragg wavelength with the changes in any of these parameters [4,5,6].

A. Temperature Change

The change in temperature ΔT operation leads to shift in Bragg wavelength $\Delta\lambda_{B/T}$ described by [4,6]

$$\Delta\lambda_B=\lambda_B\left(\alpha+\xi\right)\Delta T \quad (11)$$

Where,

$$\alpha=\frac{1}{\Lambda}\left(\frac{\partial\Lambda}{\partial T}\right) \quad (12)$$

$$\xi=\frac{1}{n_{eff}}\left(\frac{\partial n_{eff}}{\partial T}\right) \quad (13)$$

B. Strain Change

The shift in Bragg wavelength $\Delta\lambda_{B/S}$ due to the change in the applied longitudinal strain $\Delta\varepsilon_z$ is given by [5,6]

$$\Delta\lambda_B=\lambda_B\left(1-P_e\right)\varepsilon_z \quad (14)$$

Where P_e represent the effective strain-optic constant which is defined as [5,6]

$$P_e=\frac{n^2{}_{eff}}{2}\left[P_{12}-v\left(P_{11}+P_{12}\right)\right] \quad (15)$$

Where, P_{11} and P_{12} are the fiber optic strain components and υ is the Poisson's ratio [5,6].

C. Pressure Change

The shift in Bragg wavelength $\Delta\lambda_{B/P}$ due to the change in the pressure ΔP is described by [6]

$$\Delta\lambda_B=\lambda_B\left[-\frac{(1-2v)}{E}+\frac{n^2{}_{eff}}{2E}(1-2v)\left(2P_{12}+P_{11}\right)\right]\Delta P \quad (16)$$

Where E is represents the Young's modulus for the optical fiber.

4. Results and Discussion

The simulation was carried out by assuming a single-mode optical fiber with a uniform Bragg grating using MATHCAD software. Table 1 show the parameters are used in the simulation.

Table 1. Typical values for the FBG simulation parameters

Parameters	Symbols	Values
Grating length changes	L_g	1-10 mm
Bragg wavelength	λ_B	1550 nm
Effective refractive index	n_{eff}	1.45
Grating period	Λ	nm

4.1. Bandwidth of the FBG Sensors

There are several definitions for the grating bandwidth. However, the most easily identifiable one is that the bandwidth for the uniform FBG is obtained as the width between the first zeros on either side of the maximum grating reflectivity and is usually measured at the Full Width Half Max (FWHM) spectra. The FWHM denotes the bandwidth with 50% reflectivity (3-dB bandwidth) [6].

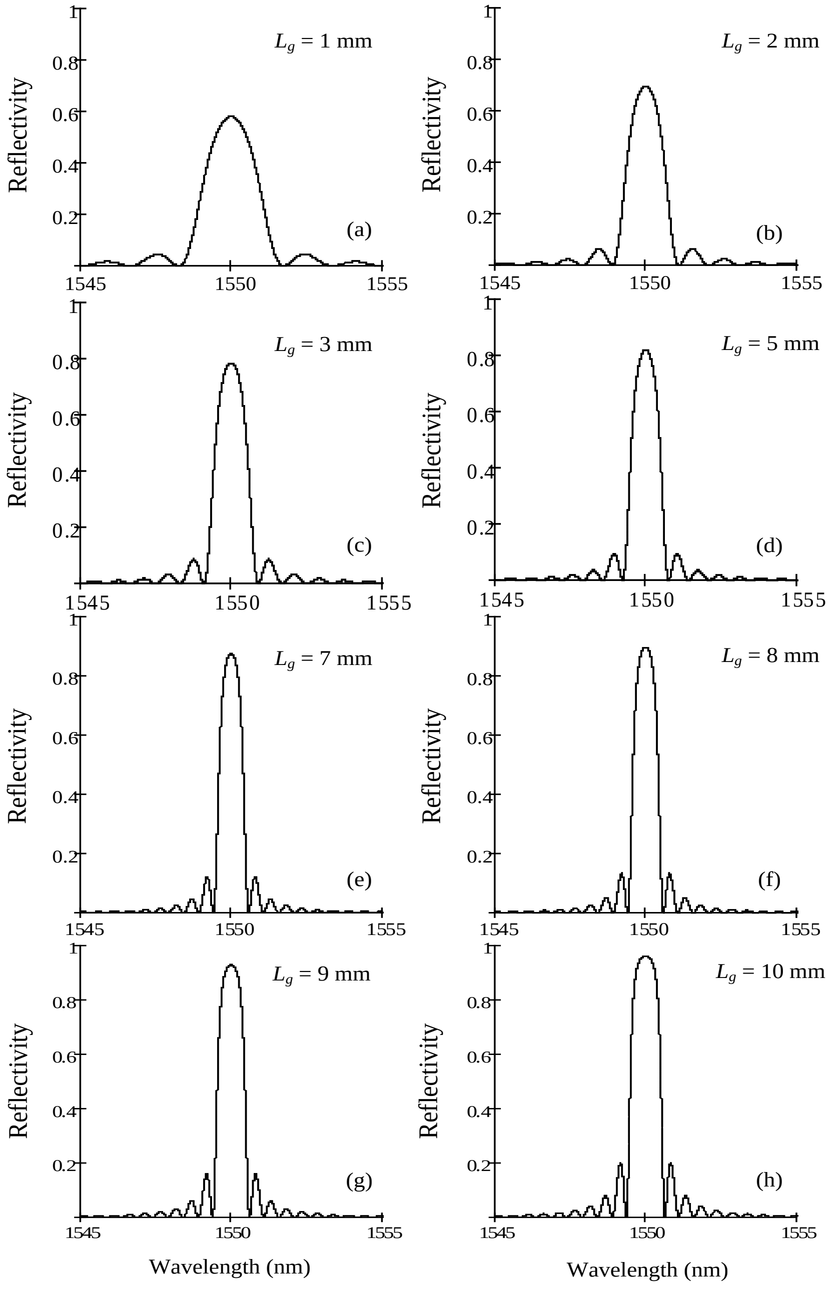

Figure 1. Reflectivity characteristics of FBG sensors for different grating length values

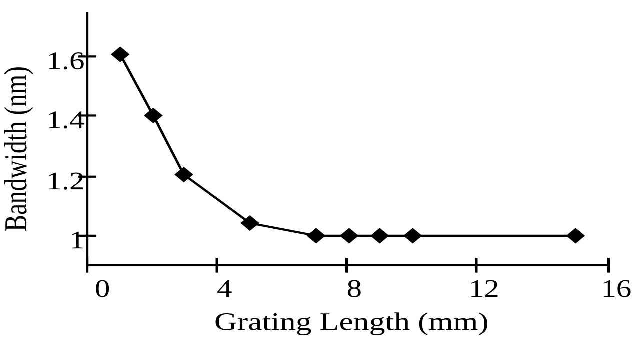

Figure 2. Relationship between FBG sensor bandwidth and grating length

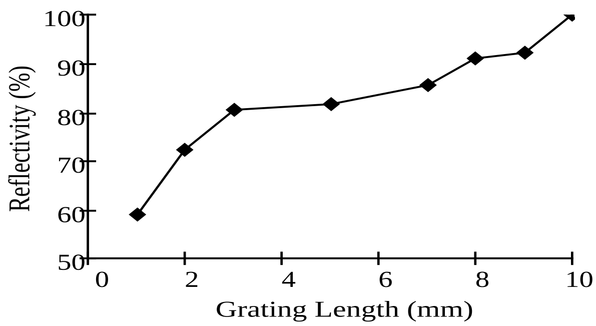

Figure 3. Relationship between FBG sensor reflectivity and grating length

A. Dependence of FBG Sensors Bandwidth on grating length

To examine how the bandwidth of the FBG sensors is influence by the change of the length (L_g) of the grating fiber, the FWHM is commonly used to elucidating the change of bandwidth. Figure 1 shows the reflectivity characteristics of a uniform FBG as a function of wavelength for different L_g values. As shown in Figure 1 (a), the case of a 1 mm sensor grating length, the 3-dB bandwidth is 1.6 nm. The bandwidth is reduces to 1.4 nm at L_g = 2 mm. And then, the bandwidth reduced again to 1.2 nm as L_g increased to 3 mm. When L_g = 5 mm, the FWHM be 1.04 nm. The 3-dB bandwidth did not change significantly after L_g of 7 mm and is maintained at 1.0 nm for 10 mm. Also, from the graphs are clearly shows that the 3-dB bandwidth has decreased exponentially with increasing L_g, and when the grating length was 7 mm, the 3-dB bandwidth is 1.0 nm and maintained subsequently for longer length, as shown in Figure 2. Conversely, the reflectivity of the uniform FBG sensors increases with the increase of the grating length as shown in Figure 3. When the grating length L_g = 1 mm, 2 mm, 3 mm, 5 mm, 7 mm, 8 mm, 9 mm and 10 mm the maximum reflectivity is 58.83%, 72.23%, 80.39%, 81.88%, 85.7, 91,43, 92.1 and 99.98%, respectively.

B. Dependence of FBG Sensors Bandwidth on Fiber Refractive Index

Figure 4 shows the effect of refractive index change (δn) on the FWHM (i.e. the 3-dB bandwidth) characteristics of a uniform FBG sensors for different L_g values. It can be observed that the 3-dB bandwidth increases with the increase of δn value and this increment significantly increases by increasing the L_g value. It can be seen that when the L_g is 1 *mm* (Figure 4 (a)), the change in the 3-dB bandwidth is less than 2 nm and this change is increases to more than 5 nm when L_g increase to 10 mm (Figure 4 (h)) with δn change from 0 to 10 x 10^{-4}. The effect is approximately linear especially with increasing L_g as shown in Figure 5. The change in the fiber refractive index leads to shift in the center Bragg wavelength and this effect is used for calculating the external perturbations like temperature, strain, pressure etc.

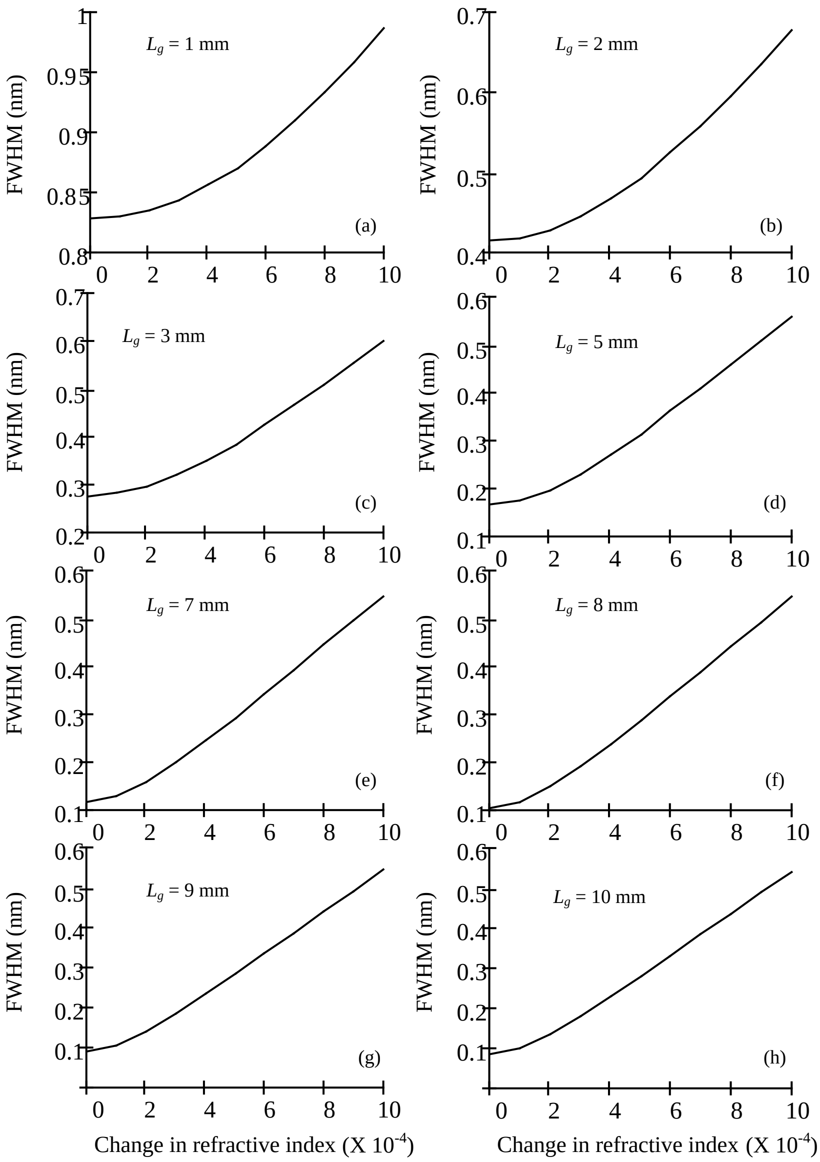

Figure 4. Effect of the refractive index change on the FWHM of FBG sensors for different grating length values

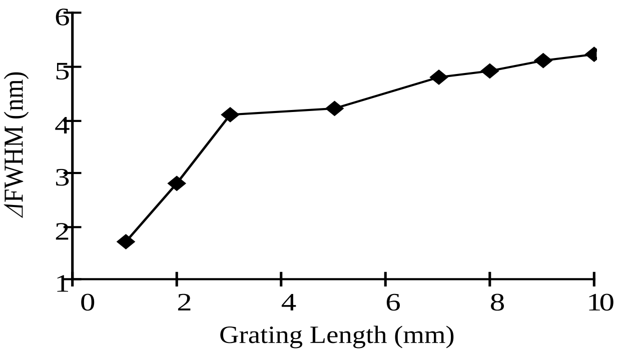

Figure 5. Rate change in the FBG sensors bandwidth with *δn* change from 0 to 10 x 10^{-4}

5. Conclusion

The characteristics of FBG sensors bandwidth for oil and gas applications are investigated successfully. The effects of fiber grating length (L_g) and the change in the fiber refractive index (δn) on the FBG sensors bandwidth are analysis numerically using MATHCAD software. It is found that; larger bandwidth can be achieved with smaller L_g value. Thus, for a strong grating with a large bandwidth to be achieved, L_g has to be small and δn must be large. However, for a strong grating with smaller bandwidth, L_g must be long and δn must be small. These analyses give a better understanding of the relationships of the FBG bandwidth characterization and it help a suggests possible ways of designing high performance FBG sensors for oil and gas applications.

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