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Control and Measurement of Pressure, Temperature, and Strain Variation by Modeling Bragg Sensor

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Abstract— **Recently, Fiber Bragg Grating Sensor (FBGS) becomes the optical technology the most used for several applications such as Structure Health Monitoring (SHM). In particular, FBGS represents the key sensing component, since it gives us the opportunity to detect many parameters: temperature, rotation, vibration and pressure. In this paper, we describe the basic principle of monitoring through FBGS, mainly we are interested on the variation of pressure, strain and temperature. Measurements of pressure along the optical fiber can be obtained by recurring to two methods which will be explaining along this paper.**

***Index Terms*— Optical measurement, FBGS, Pressure, Strain, temperature.**

I. Introduction

During tens of years, electrical sensors were used as standard mechanism to measure physical and mechanical phenomena. However, these sensors have certain inherent limitations such as transmission loss and susceptibility to electromagnetic interference (noise) which make their use more complicated or difficult practice within many applications. Fiber optical sensors are an excellent solution to meet these challenges, using light rather than electricity and fiber optical standards rather than copper cables. The Innovations that have been multiplied in the last 20 years in industries optoelectronic communications and fiber optical have considerably reduced the cost of optical components while improving their quality. The optical fiber sensors have moved from experimental research applications laboratory in an application and a more widespread use in the context of field applications such as structural health monitoring [1].

II. Theory

A. Optical Fiber Sensor

Optical Fiber Sensor is classified to three big categories: Interfermetric, Distributed sensors (Raman, Brillouin and Rayleigh distributed sensors) and Grating-based Sensors. In this article, we are especially interested on Grating-based Sensors precisely Fiber Bragg Grating Sensors (FBGS), Fig.1 summarizes the pervious description:

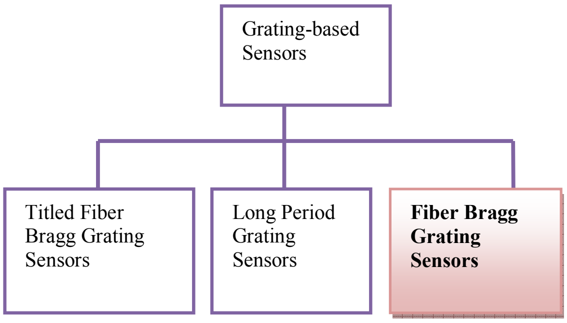

Fig. 1 Categories of Grating-based Sensors

Both Long Period Grating Sensors (LPGS) and Titled Fiber Bragg Grating Sensors (TFBGS) have no reflection sensing spectra, thus the sensing system using LPGS and TFBGS is more complex as compared with the reflective sensors (FBGS). FBGS have a high resistance and sensitivity, small size, lightweight, temperature immunity… Therefore, FBGS can measure high temperature (>700ºC), very high strain (>10.000µm/m) and pressure from 10^{-12}Pa [8] for an extreme vacuum up to 10^{12} Pa. As well FBGS are not distance-dependent up to 50 Km [7].

B. Bragg grating sensor

The basic principle commonly used in FBG sensors is to monitor the shift in the Bragg wavelength of the FBG under test where changes in the strength of the measurand are translated into modulation of the grating structure. Fiber grating is a sensitive optical device, when uv irradiates, the refractive index of fiber core varies periodically along the axis leading to variation in its spectral characteristics [1]. The FBG Bragg wavelength under no load is given by

Schematic structure of a fiber Bragg grating (FBG).

$$\lambda_B = 2\eta\Lambda$$

Where η is the refractive index of fiber core

Λ is the grating pitch (the period of fiber grating)

$\Lambda=\Lambda_0(1+\varepsilon_z)$

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$$\varepsilon_z = \frac{N\lambda_{B0}}{2\eta_{eff}L}$$

L is the fiber length under strain
N the Number of fringes
The following figure (Fig.2) is an overview

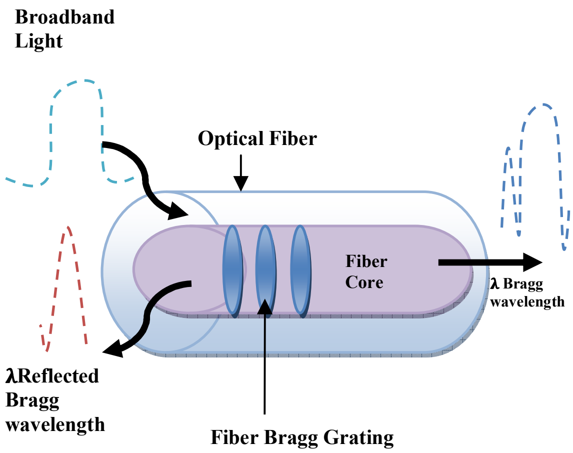

Fig. 2 View of a FBG Optical Sensor

FBGS can be manufactured with various Bragg wavelengths (λ_{B0}), which enables different FBGS to reflect unique wavelengths of light λ_B [6]. Using OptiSystem we can measure this various signals: the pump laser signal, the Fiber Bragg Grating Signal and the reflected Bragg Signal. OptiSystem has a special component which gives us sophisticated measurement such as power meter, the optical spectrum, etc. In our case, we chose here to work with a pump laser (Frequency=1550nm, Power=0.1 W), Optical Fiber (Length=50Km and Attenuation=0.2dB/Km), Fiber Bragg Grating (Frequency=193.1 THz, Effective index=1.45, Length=2mm). In order to have real terms, we add a connector which has a insertion loss equal to 0.2dB/Km.

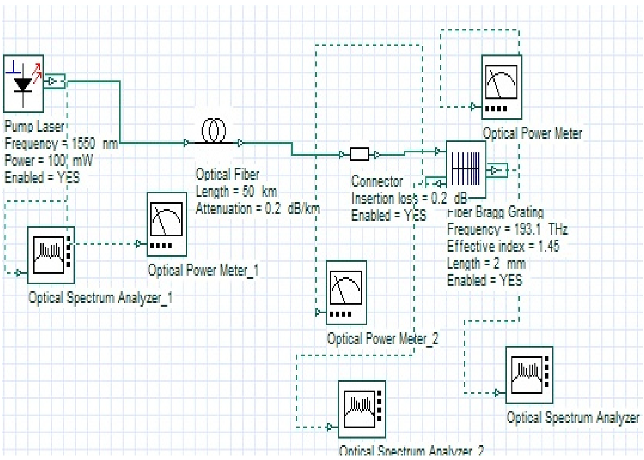

Fig. 3 An Expanded View of simulation FBGS using OptiSytem

The three Optical Spectrum Analyzer used here, show that the variation of the different signal power according to the frequency variation.

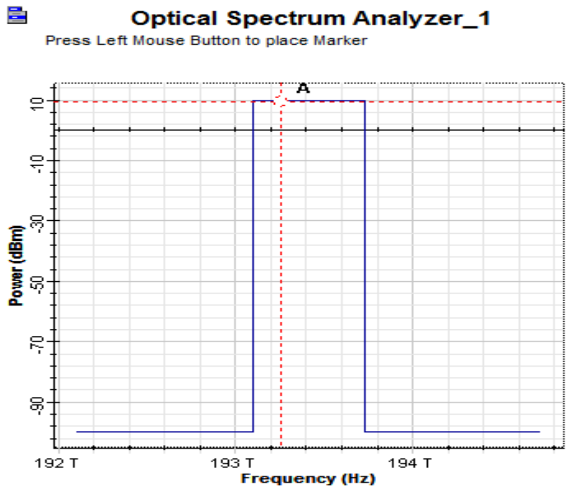

Fig. 4 The Optical Power Spectrum of : Pump Signal

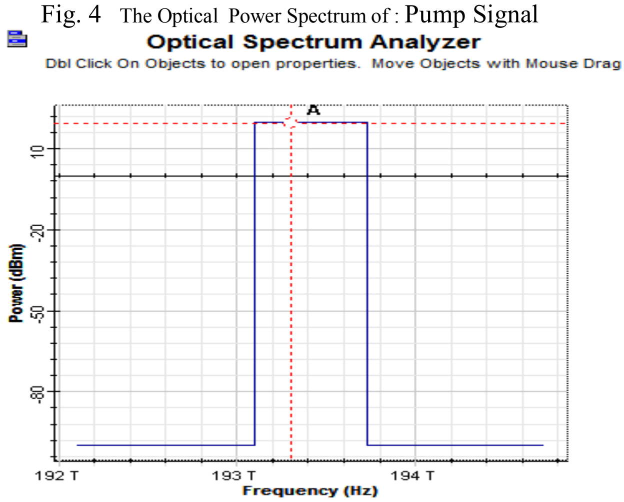

Fig. 5 The Optical Power Spectrum of : Fiber Bragg Grating Signal

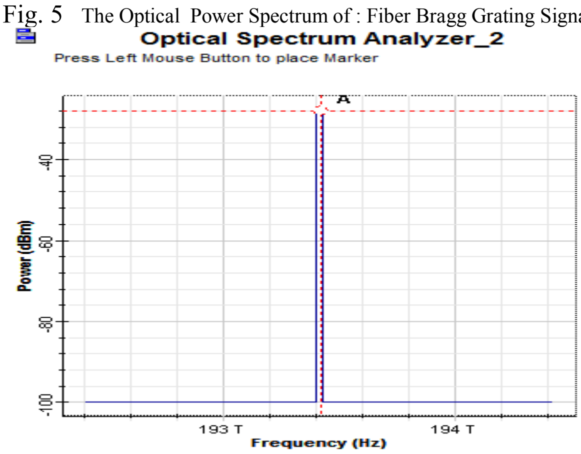

Fig. 6 The Optical Power Spectrum of : Reflected Fiber Bragg Grating

It's clearly that the pump signal, the fiber Bragg grating signal and the reflected Bragg signal have significantly different wavelengths. In the same meaning, the results obtained using Optical Power Meter, show that the reflected signal have the lowest power. This is a due to attenuation's parameter introduced in the optical fiber. The same results can be shown using the optical power meter:

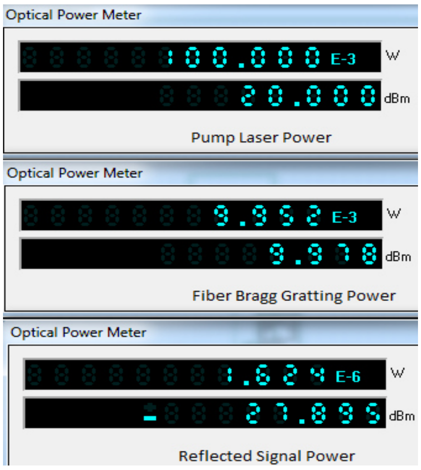

Fig. 7 Optical Power Meter

The optical power response is relatively linear to the wavelength shift of a uniform FBG. The wavelength shift is proportional to the elongation of the fiber grating which is generated due to the optical displacement. When we obtain the optical power of different signal, we can deduce the wavelength shift then this processing method can be used to obtain stable measurement of the vibration/temperature/pressure.

C. Temperature, Strain and Pressure Sensitivity

1. Temperature Variation

α_{glass} of the optical fiber is almost low.With α_{glass}=$0.55.10^{-6}$/K

.

The wavelength of a FBG sensor changes with temperature and strain variation:

$$\frac{\Delta\lambda}{\lambda_0} = (1-p).\varepsilon + \alpha_\delta.\Delta T$$

where $\Delta\lambda$ is the wavelrngth shift,

$\lambda_0$is the base wavelength at test start (1550nm)

p= photo-elastic coefficient ,p=0.22

ε= the strain in FBGS

ΔT = temperature variation in K

α_δ = variation of the refraction index

The first term of equation (2) (1-p).ε describes the strain impact caused by force (ε_m) and temperature (ε_T).

$$\varepsilon = \varepsilon_m + \varepsilon_T$$

ε_m: *mechanically caused strain*

ε_T: *temperature caused strain*

$$\varepsilon_T = \alpha_{sp}.\Delta T$$

where α_{sp} is the expansion coefficient per k of the specimen.

The second part ($\alpha_\delta.\Delta T$) describe the variation of the glass refraction index n due to temperature change.

$$\alpha_\delta = \frac{\delta n/n}{\delta T}$$

$$\frac{\Delta\lambda}{\lambda_0} = K.\varepsilon_m + (\alpha_\delta + \alpha_{sp}).\Delta T$$

K is the gage factor, K=0.78 [3].

When the fiber is fixed at one point, the FBGS $\Delta\lambda/\lambda_0$ signal changes only with temperautre variation ΔT.

$$\frac{\Delta\lambda}{\lambda_0} = (\alpha_\delta + \alpha_{sp}).\Delta T$$

We treat the case of α is the thermal expansion coefficient of the fiber, so $\alpha_{sp}$is the α_{glass} of the fiber.

$$\Delta T = \frac{1}{k.\alpha_{glass}+\alpha_\delta}.\frac{\Delta\lambda}{\lambda_0}$$

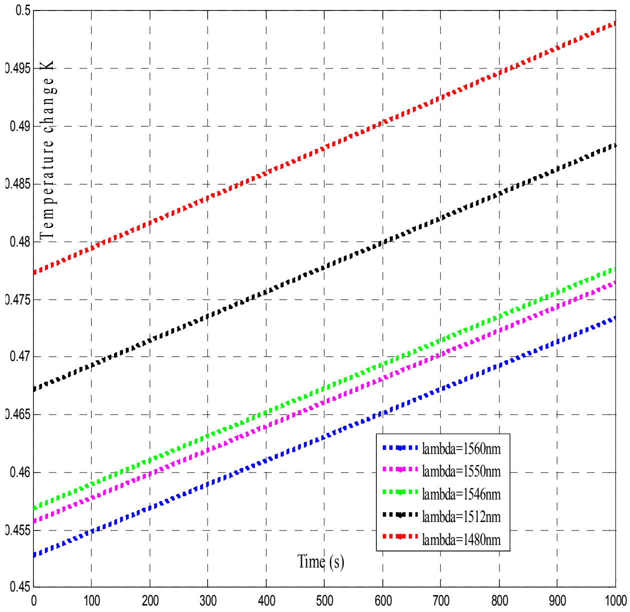

Fig. 8 Temperature Variation

The resultats explain that the temperature change ΔT dependent specially on the FBGS signal $\Delta\lambda/\lambda_0$. At λ_0=1550nm we obtain a temperature variation between 0.453-0.467.

2. Strain Variation

In the case of optical fiber is fixed to a specimen, the FBGS signal $\Delta\lambda/\lambda_0$ vaies with the strain.We are interessed here to many point in the fiber. So the Bragg Wavelength shift with temperature and stain shift can be written [4]:

$$\frac{\Delta\lambda}{\lambda_0} = (1 - \frac{\eta^2}{2}[\rho_{12} - V(\rho_{11} - \rho_{12})])\Delta\varepsilon + (\alpha + \xi)\Delta T$$

Where $\Delta\varepsilon$: the strain variation

ρ_{ij}: the coefficient of Pockel of the stress-optic tensor

V : Poisson's ratio

α :coef.of thermal expansion

ξ the thermo-optic coefficient

ΔT temperature change

The perturbation of strain and temperature are approximately linear to the shift in bragg wavelength.

Thus, strain-induced FBGS signal $\Delta\lambda/\lambda_0$can be expressed as:

$$\frac{\Delta\lambda}{\lambda_0} = (1 - P_e)\,\Delta\varepsilon$$

Where P_e is the effective photoelastic constant of fiber. From this equation, we can determined the strain perturbation by measuring FBG wavelength change.

$$P_e = \frac{\eta^2}{2}[\rho_{12} - V(\rho_{11} - \rho_{12})]$$

$\eta = 1.46$, $V = 0.16$, $\rho_{11} = 0.12$ and $\rho_{12} = 0.27$, thus $P_e = 0.2213$.

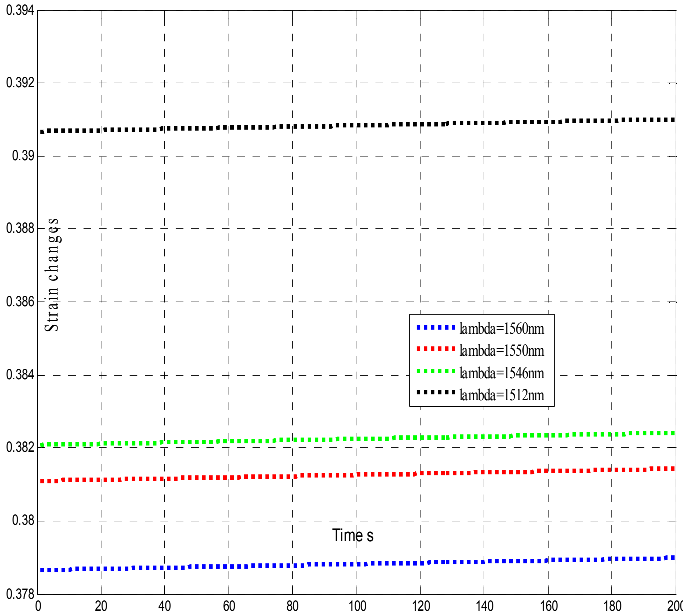

Fig. 9 Stain Variation at different wavelength

The strain variation $\Delta\varepsilon$, in a well-determined wavelength, varied very slowly (0.378-0.394).

3. Pressure Variation

Actually, FBGS have been applied in a many range of sensing applications, of these pressure measurement is considered as a major area of interest. Thus, a significant number of configurations of FBG pressure sensors have been demonstrated [5]. There are two ways to determined the pressure in FGB, whether we use the relationship pressure/ temperature or pressure/strain.

The relationship between the pressure variation applied in FBG and temperature and the Bragg wavelength $\Delta\lambda_B$is [10]:

$$\frac{\Delta\lambda_B}{\lambda_B} = K_p\Delta P + K_T\Delta T$$

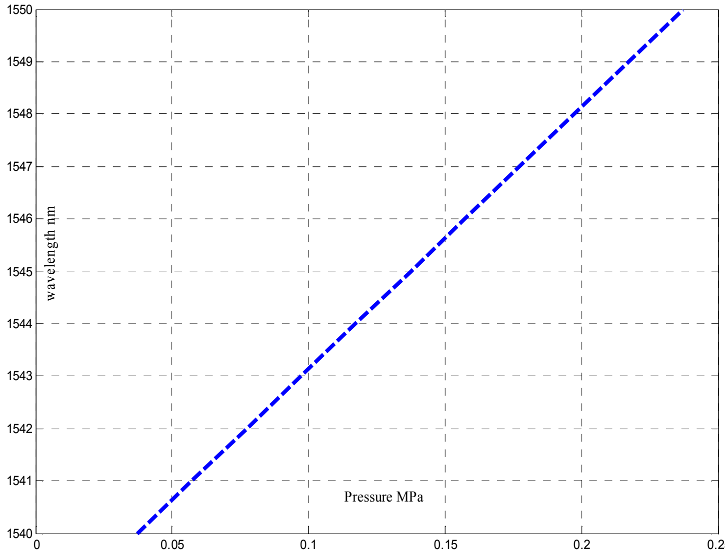

Fig. 10 Pressure Variation at different wavelength (using the approximately of Wen-Fung Liu)

The wavelength shift used in our case is 0.587nm.

Therefore, pressure variation can be determined using the relationship between pressure applied in FBG and strain

$\varepsilon = \frac{P(1-2V)}{E}$ Where

ε : The axial strain

P : FBG Pressure applied

V : Poisson's ratio (0.16)

E : Young's modulus of the polymer (7.10^{10} N/m^{-2})

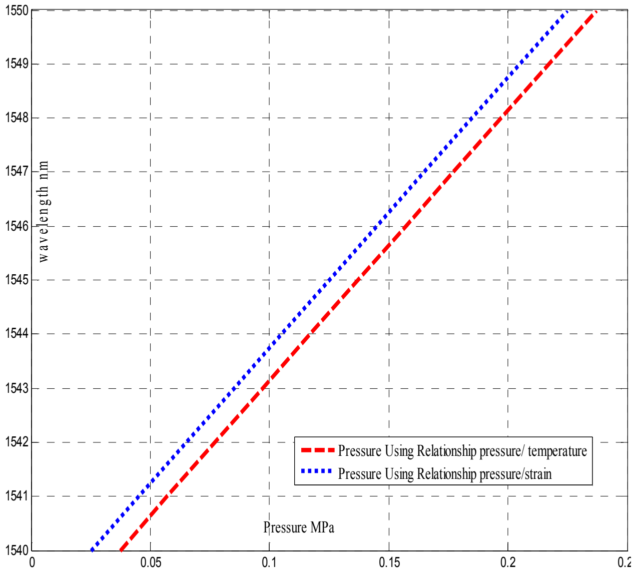

Fig. 11 Pressure Variation

When we already known pressure and temperature' sensitivities of FBGS, then we can measure the pressure by using relationship pressure /temperature or pressure/ strain. Further, using these methods we obtain related results (see Fig.9).

III. Conclusion

In this paper, it has already been explained the basic principle of monitoring through FBGS which can be manufactured with various Bragg wavelength. It has been shown that we can determine temperature, strain and pressure measurements when we obtained the wavelength shift. Using Optisystem we have demonstrated that it's possible to module the optical spectrum which give us the opportunity to monitor all FBG. Owing to it's good linearity, FBGS can measure the pressure recurring to temperature and strain sensitivites. This has been demonstrated that both methods gives results different from few 0.02 MPa.

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