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Modelling and Simulation of Pressure Sensitivity of Bragg Grating Sensor for Structural Health Monitoring Application

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Abstract - Here in this paper we presented the modelling of FBG as pressure sensor for structural health monitoring application is geometrically designed in the wavelength window of 1.568-1.580µm. Simulation has been done by using optical software R-Soft (GratingMOD).

***Keywords* - FBG, SHM, GratingMOD, Pressure.**

1. Introduction

Modelling and simulation are mathematical models that allow representing the dynamics of the system via simulation, allows exploring system behaviour in an articulated way which is often either not possible, or too risky in the real time. Fibre Bragg grating (FBG) sensors have been investigated intensively in the past few years due to its small size and robustness, ease of fabrication, suitability for use in multiplexed sensor networks and smart structures [2]. In this paper we represent the modelling of FBG for pressure sensor for structure health monitoring.

1.1 Fiber Bragg Grating

Consider a uniform Bragg grating formed within the core of an optical fibre with an average refractive index *n*0. The index of the refractive profile can be expressed as

$$n(z) = n_0 + \Delta n \cos\left(\frac{2\pi z}{\Lambda}\right) ...(1)$$

Where Δn is the amplitude of the induced refractive index perturbation (typically 10^{-5} to 10^{-2}) and z is the distance along the fibre longitudinal axis. Using coupled-mode theory [1] the reflectivity of a grating with constant modulation amplitude and period is given by the following expression

$$R(l,\lambda) = \frac{k^2 \sinh^2(sl)}{\Delta\beta^2 \sinh^2(sl) + s^2 \cosh^2(sl)} ...(2)$$

where $R(l,\lambda)$ is the reflectivity, which is a function of the grating length l and wavelength λ . k is the coupling coefficient, $\Delta\beta=\beta-\pi/\Lambda$ is the detuning wave vector, $\beta=2\pi n_0/\lambda$ is the propagation constant and finally $s^2 = k^2 - \Delta\beta^2$. For sinusoidal variations of the index perturbation the coupling coefficient, k, is given by

$$k = \frac{\pi\Delta n}{\lambda} M_{Power} ...(3)$$

Where M_{power} is the fraction of the fibre mode power contained by the fibre core. In the case where the grating is uniformly written through the core, *Mpower* can be approximated by $1-V^{-2}$, where V is the normalized frequency of the fibre, given by

$$V = (2\pi/\lambda)a\sqrt{n_{co}^2 - n_{cl}^2} ...(4)$$

Where a is the core radius, and nco and ncl are the core and cladding indices, respectively. At the centre wavelength of the Bragg grating the vector detuning is $\Delta\beta = 0$, therefore the expression for the reflectivity becomes

$$R(l,\lambda) = \tanh^2(kl) ...(5)$$

The reflectivity increases as the induced index of refraction change gets larger. Similarly, as the length of the grating increases, so does the resultant reflectivity.

1.2 Structural Health Monitoring

A typical health monitoring system is composed of a network of sensors that measure the parameters relevant to the state of the structure and its environment [2] Nowadays structural health monitoring is a

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fundamental tool to assess the behaviour of existing structures but also to control the performance of large new structures, foreseen to give information to monitor their lifetime. In this paper, the monitoring of pressure with optical fibre bragg grating sensors recorded in standard single mode optical fibers. Since FBG sensors are an all-in-fibre technology, they take advantage of the optical fibre properties, presenting also advantages over traditional electronic sensors due to the possibility to multiplex a large number of different sensors (temperature, displacement, pressure, pH value, humidity, high magnetic field and acceleration) into the same optical fibre, reducing the need for multiple and heavy cabling used in traditional electronic sensing.

2. Grating MOD

R-Soft is an optical simulator in which one of the tools GratingMOD is used for design and simulation of grating [3]. Any type of waveguide structure that can be defined in the R-Soft CAD interface can be treated as perturbed or, unperturbed waveguide in GratingMOD. Perturbation can be applied to index, width, height and both in combination. GratingMOD can simulate multiple types of grating profile and also can include multiple apodization types. Analysis and Synthesis are the two tools for simulation which facilitate to complete information of light wave field inside core of the fiber with gratings. Analysis simulation gives the information of reflectivity and transmitivity, modes, B.W.

- GratingMOD derived *via* couple mode theory based on orthogonal modes.
- Report has been compiled to understand the CAD Tool for Fiber Bragg Grating Sensor.
- MATLAB Simulation.

3. Simulation

The FBG sensors were designed with core diameter 8 µm with refractive index of 1.47, and cladding diameter 125 µm with refractive index 1.44.The gratings were inscribed over a length of about 3000 µm. The magnitude of the photo-induced periodic modulation of refractive index inside the core is generally of the order of $10^{-5} – 10^{-2}$. The grating periodicity produced with this phase mask was approximately Λ=0.5365µm and N_{eff}= 1.464926 giving a baseline Bragg wavelength around 1.57174 nm.

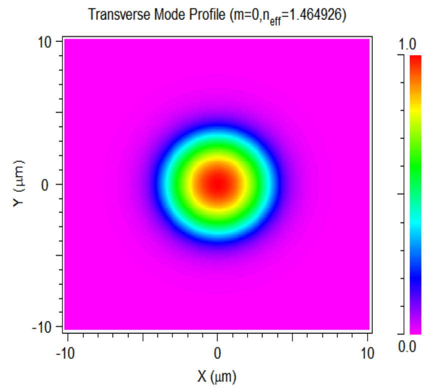

Fig1.Computed modes for the Bragg grating

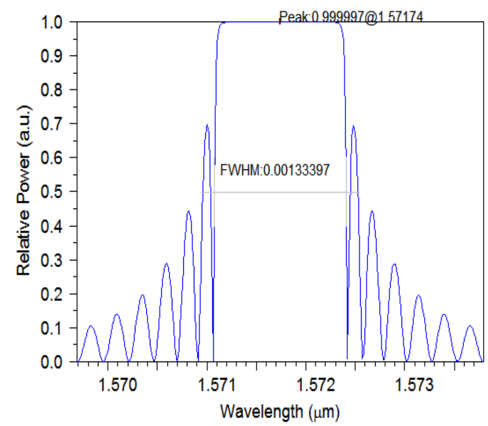

Fig2. Computed reflection spectra Bragg wavelength at 1.57174µm

Reflectivity increases as Grating length increases. For short period grating, concluded in paper [2], that for sensor application the reflectivity should be narrow spectral width. The effect of elongating the optical fibre and thus the grating pitch has been simulated by taking the output graphs by varying the grating pitch from 0.5365µm to 0.540µm in regular intervals of 0.00035µm. Simulation results in the form of graphs of reflected power as a function of wavelength. From iterations it has been established that at a grating pitch of 0.5365µm, maximum reflected power is recorded at wavelength of 1.550µm.

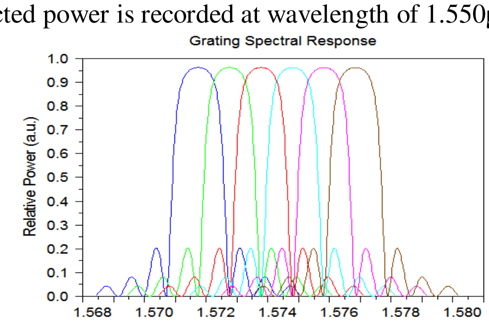

Fig3-Grating periodicity produced with this phase mask was approximately Λ=0.5365µm

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4. Pressure Sensitivity

The core effective index of refraction and the periodicity of the grating determine its center wavelength so that the change of fiber with pressure will affect its Pitch[4].

Basic Principle of FBG as a Sensor
Braggs Condition

$$\lambda B = 2neff\Lambda$$

Due to external perturbation that is Pressure there is a shift in the Bragg wavelength.

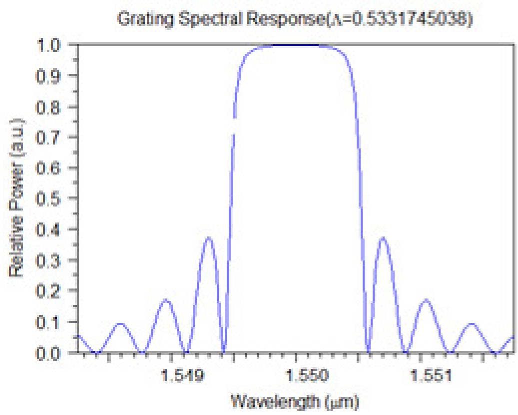

Fig 4. It Has a Pitch 0.533 and Pitch Can Be Calculated Using Bragg Condition

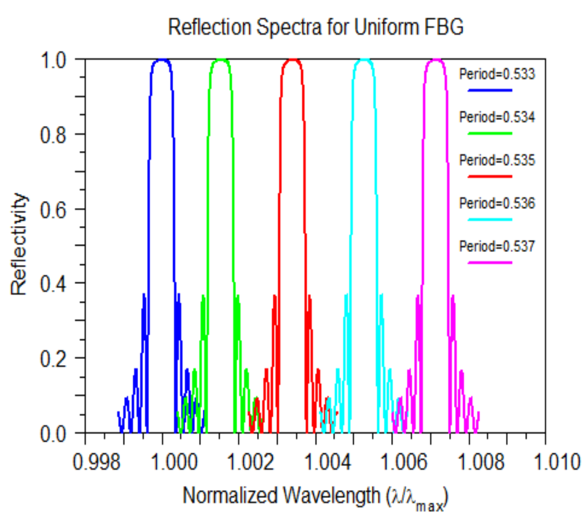

Fig 5. Reflection Spectra for Uniform FBG

As shown in all the above plot, Interrogating the wavelength at 1.55 shows the pitch variation due to presence of minimum perturbation. Varying the pitch value shown us shift in the wave length. For a grating pitch of 0.5325 µm, maximum reflected power was recorded at a wave-length of 1550 nm. FBG sensors are based on the fact that the Bragg wavelength changes with change in the pitch of the grating and the change in the refractive index.

Table 1: Pitch Vs Wavelength

Pitch (□)	wavelength
0.533	1.550
0.534	1.552
0.535	1.555
0.536	1.558

As shown in all the above plot, Interrogating the wavelength at 1.55 shows the pitch variation due to presence of minimum perturbation. Varying the pitch value shown us shift in the wave length. For a grating pitch of 0.5325 µm, maximum reflected power was recorded at a wave-length of 1550 nm. FBG sensors are based on the fact that the Bragg wavelength changes with change in the pitch of the grating and the change in the refractive index.

Pressure Sensing code for analyzing the change in Strain for the applied pressure.

Axial Strain along FBG due to applied pressure 'P' is given by,

$$\varepsilon = -\frac{P(1-2v)}{E} \quad ...(9)$$

ε - Strain, P- Pressure, v- Poison Ratio, E- Young's Modulus

```
CLC;
CLOSE ALL;
CLEAR ALL;
Pressure=0e6:0.5e6:100e6; %RANGE OF PRESSURE VALUES IN MPA
v=0.37; %POISSON RATIO
E=2.2e9; %YOUNG'S MODULUS
Eps=-[Pressure*(1-2*v)/E]; %PRESSURE SENSING EQUATION
plot(Pressure, Eps),grid; %PLOTTING FUNCTION
title('Pressure Vs Strain ');
```

```
xlabel('Pressure (MPa)');
ylabel(' Strain (μm)');
```

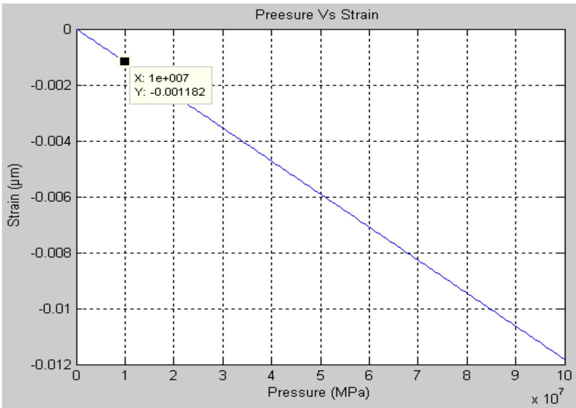

Fig6- Depicts the Change in Strain with Change Pressure

Pressure Sensing code for analyzing the change in wavelength for the applied pressure.

```
CLC;
CLOSE ALL;
CLEAR ALL;
P11= 0.113; %COMPONENTS OF STRAIN OPTIC
TENSOR
P12= 0.252; %COMPONENTS OF STRAIN OPTIC
TENSOR
NEFF=1.482; %EFFECTIVE REFRACTIVE INDEX
V=0.33; %POISSON RATIO
PE= ((((NEFF) ^2)/2)*(P12-V*(P11+P12))); %STRAIN
OPTIC CONSTANT
LAMBDAB=1550*10^-9; %BRAGGS CENTER
WAVELENGTH
E= [0.000068, 0.000171, 0.0003166, 0.0005283];
%STRAIN VALUES
P= [0.012, 0.021, 0.05, 0.054]; %PRESSURE VALUES
IN MPA
DELTALAMBDA=LAMBDAB*(1-PE)*E;
%PRESSURE SENSING EQUATION
PLOT (P, DELTALAMBDA); %PLOTTING FUNCTION
GRID;
XLABEL ('PRESSURE IN MPA');
YLABEL ('SHIFT IN WAVELENGTH ');
```

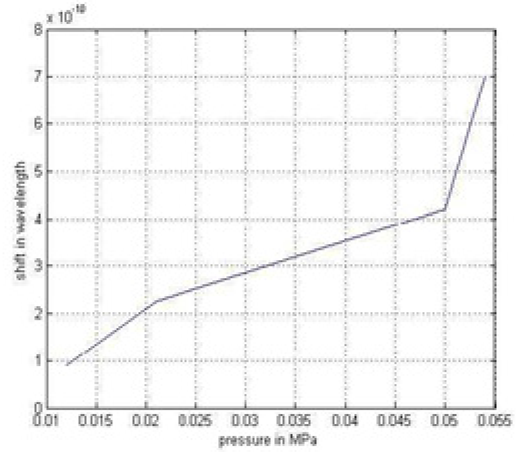

Fig 7. Depicts the Change in Wavelength with Change Pressure

5. Conclusion

Simulation results show the design parameter at L=1500μm, reflectivity 97.26% and FWHM =1.04nm for optical sensor by using mod-grating toolbox to achieve narrow spectral response which is very much required for high sensitivity. The modelled simulated parameters implemented for Strain sensor in the range of 1-10με for structural health monitoring.

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[3] optics.synopsis.com/RSoft/GratingMOD
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