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

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Abstract

Here in this paper we presented the modelling of Fiber Bragg Grating (FBG) as temperature 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, Temperature.

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 Fibre Bragg grating (FBG) for temperature sensor for structure health monitoring. Fiber gratings are nowadays usually fabricated by a variant of the transverse holographic method first proposed by Meltz et al.[5]. In this paper in order to design fiber gratings for various applications, it is crucial to have tools for analysis, synthesis and characterization of fiber gratings. The most common mathematical model that governs wave propagation in gratings is the coupled-mode theory [6].

2. Fiber Bragg Grating

Consider a uniform Bragg grating formed within the core of an optical fibre with an average refractive index n0. The index of the refractive profile can be expressed as

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

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.

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

where R(l,λ) is the reflectivity, which is a function of the grating length l and wavelength λ . k is the coupling coefficient, Δβ=β-π/Λ is the detuning wave vector, β=2πn0/λ is the propagation constant and finally s2 = k2-Δβ2. For sinusoidal variations of the index perturbation the coupling coefficient, k, is given by

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

Where Mpower 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

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

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 Δβ = 0, therefore the expression for the reflectivity becomes

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

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.

3. 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 fundamental tool to assess the behaviour of existing structures but also to control

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the performance of large new structures, foreseen to give information to monitor their lifetime. In this paper, the monitoring of temperature 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. SHM of a structure performs structural characterization and damage detection over time in order to provide reliable information regarding the integrity of the structure. SHMS for a structure consists of sensors and transmission cables, data acquisition systems, data transfer and storage systems, data management that normally includes data analysis as well as presentation, and data interpretation. It is a valuable implement, in general a permanent system that can provide many different solutions and outputs depending on the monitored structure and requirements based on the system itself. Larger projects also have a Control Room with permanent crew in order to take actions if needed. More info about SHM and monitoring concepts can be seen in [7]. The concept of structural health monitoring (SHM) stands to reduce the complexity and the costs associated with these traditional approaches, and the exploitation and implementation of SHM tools are expected to replace schedule-based inspections by the on-board and real-time monitoring to reduce platform life cycle cost, improve safety and reliability, and extend operational life cycle [8].

4. GratingMOD

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.

FBG Created With GratingMOD Utility

Objective: Change the index modulation depth of FBG and get changes in reflection spectra. Substitute all parameters value using GratingMOD layout generator.

Table 1: Assigning the Values for Parameters to Generate and Simulate

Simulation tool	Grating MOD
Profile type	Step index, single
Structure type	Fiber
Grating type	Volume index
Modulation depth	0.0012
Waveguide width	5.25 µm
Waveguide height	5.25 µm
N	4000
Period	0.5
Length	N*period=2500

5. 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 Neff= 1.464926 giving a baseline Bragg wavelength around 1.57174 nm.

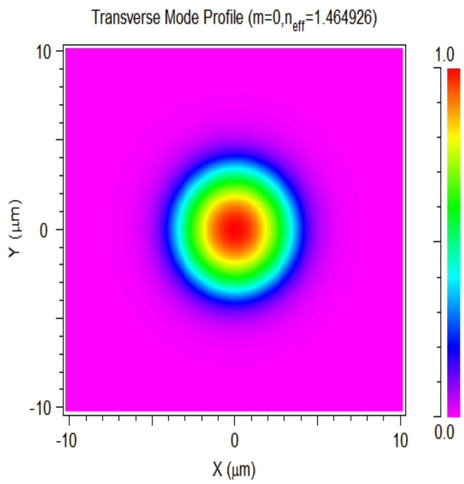

Fig 1: Computed modes for the Bragg grating

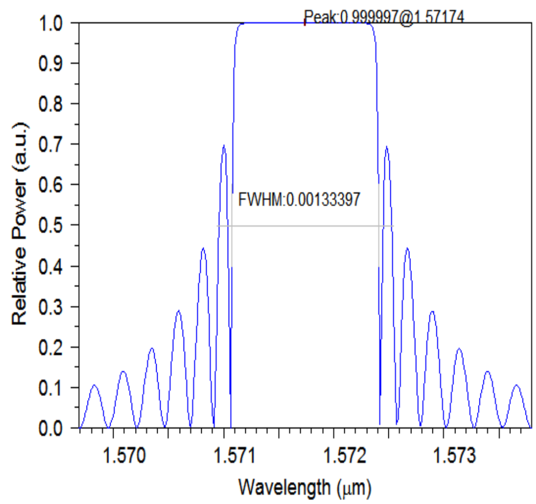

Fig 2: Computed reflection spectra Bragg wavelength at 1.57174µm

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.

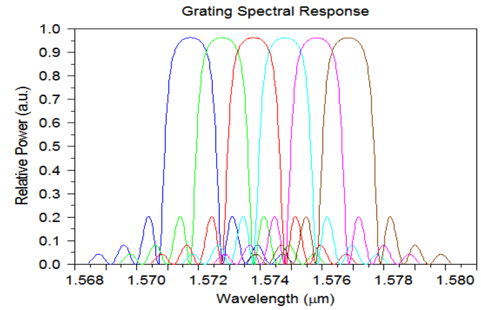

Fig 3: Grating periodicity produced with this phase mask was approximately Λ=0.5365µm

I. Temperature Sensitivity

There is a shift in the wavelength because of the thermal expansion changes the grating period and the index of refraction. This fractional wavelength shift for a temperature change [4]

$$\Delta\lambda_{B(T)} = \lambda_B(\alpha+\xi)\Delta T \text{........(6)}$$

$$\Delta\lambda_{B(T)} = \lambda_B\left(\frac{1}{\Lambda}\frac{d\Lambda}{dT}+\frac{1}{n_{eff}}\frac{dn_{eff}}{dT}\right) \text{...... (7)}$$

Where in LHS, first parameter thermal expansion coefficient, $\alpha = \frac{1}{\Lambda}\frac{d\Lambda}{dT}$ =0.55*e*-6 (for silica) Second parameter thermo optic coefficient, $\xi = \frac{1}{n_{eff}}\frac{dn_{eff}}{dT} = 8.6e-6$ (Germania-doped silica core)

As we know from literature survey that FBG works on the principle of wavelength shift causes change in the grating period either effective refractive index of the core and temperature sensor not dependent only the thermo-optic but also depend on the thermal expansion. From equation (7), changes in the period due to temperature cause elongation in the fibre i.e. nothing but thermal expansion.

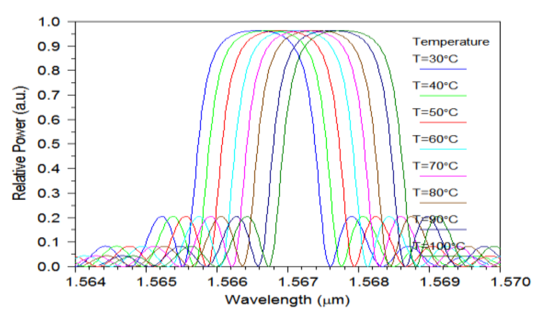

Fig 4: wavelength shift as a function of temperature

From equation (8), the expected sensitivity at a ~1.55µm Bragg grating is approximately ~13.7nm/°C. In this paper, temperature range has been chosen for the range of 30-100°C. Fig3 provides the simulated results of a Fiber Bragg Grating centre wavelength shift as a function of temperature.

6. 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 temperature sensor in the range of 30-100°C for structural health monitoring.

Future Scope

This work can be further extended for simultaneous measurement of pressure and temperature by different types of packaging on the same fiber bragg grating specific like length, width, FHM, apodization already simulated and we can also extended this work as a bio sensor.

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