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Fibre Bragg grating strain sensor and study of its packaging material for use in critical analysis on steel structure

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ABSTRACT

Strain studies in civil structures, aircrafts, oil pipelines, etc. are pivotal in avoiding unexpected failures. Long-term strain study of structures also helps in setting the design limits of similar structures. Conventionally, most structures rely on maintenance schedules, visual inspection and a few conventional sensors. But the high cost of maintenance, lack of precision in visual inspection and susceptibility of sensors to harsh environmental conditions have made structural health monitoring (SHM) a necessity.

Over the past few decades, fibre Bragg grating (FBG) sensors have emerged as a suitable, accurate and cost-effective tool in SHM. Fibre Bragg gratings are obtained by creating periodic variations in the refractive index of the core of an optical fibre. These periodic variations are created by using powerful ultraviolet radiation from a laser source. Periodic structure acts as a Bragg reflector of particular wavelength. Minute change in the periodic structure due to external perturbation will cause appreciable wavelength shift. This shift in turn can be translated to measurand related to perturbation. The main advantages of FBGs over other optical sensor schemes are its low cost, good linearity, wavelength multiplexing capacity, resistance in harsh environments and absolute measurement. FBG sensor technology is now on the verge of maturity after almost two decades of active research and development in this field. Efforts are now concentrating on delivering complete FBG sensor systems including front-end electronics.

This paper demonstrates with the aim to provide different design and experimental packaging procedures of indigenously developed FBG sensors for strain measurement. Various model of loading on FBG have been tried to explore with particular attention on the primary packaging of the sensor for application on steel cantilever structure and cement concrete. Preliminary packaging has been done with composite materials such as epoxy resin casting and fibre reinforced plastic (FRP) composites. Encouraging results are obtained and presented in this paper. The results are compared with the standard FBG sensors and with mechanical strain gauge.

1. Introduction

Strain studies in civil structures, aircrafts, oil pipelines, etc. are pivotal in avoiding unexpected failures. Long-term strain study of structures also helps in setting the design limits of similar structures. Conventionally, most structures rely on maintenance schedules, visual inspection and a few conventional sensors. But the high cost of maintenance, lack of precision in visual inspection and susceptibility of sensors to harsh environmental conditions has made structural health monitoring (SHM) a necessity. Over the past few decades fibre Bragg grating (FBG) sensors have emerged as a suitable, accurate and cost-effective tool in SHM.

The main advantages of FBGs over other optic sensor schemes are its low cost, good linearity, wavelength multiplexing capacity, resistance in harsh environments and transduction mechanism which eliminates the need for referencing as in interferometric sensors. FBG sensor technology is now on the verge of maturity after almost two decades of active research and development in this field. Efforts are now concentrating on delivering complete FBG sensor systems including front-end electronics.

Several review papers on fibre Bragg grating applications have been published [1–4]. Strain and temperature have so far been the dominating measurand of interest [5–7]. Author is also made a critical review on structural vibration using FBG and Fabry–Perot sensors [8]. Recently the authors' reviewed [9] the previous work of FBG as strain sensors in structural health monitoring including the present status and applications along with various encapsulation techniques.

FBG's are basically strain and temperature sensitive devices. Bragg gratings can be inscribed directly in a standard optical fiber at

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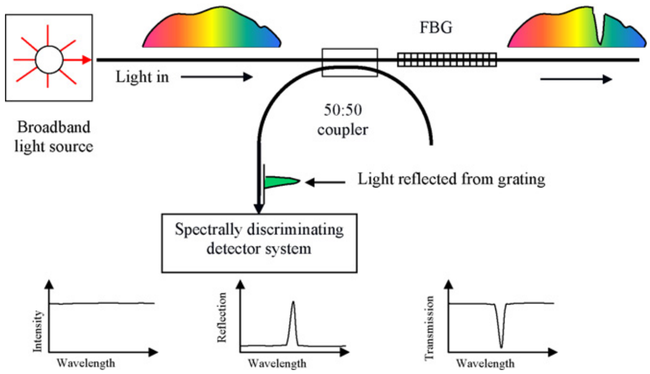

Fig. 1. Transmission and reflection spectra from an FBG [14].

any position, and several of them can be configured in series or parallel on different fibers and interrogated from the same light source enabling flexible sensor configurations. This paper demonstrated with the aims to provide different design and experimental packaging procedures of FBG sensors for strain measurement. Various model of loading on FBG have been tried to explore with particular attention on the primary packaging of the sensor for application on steel cantilever structure and cement concrete.

2. Principle of operation of FBG sensors

Fibre Bragg gratings are obtained by creating periodic variations in the refractive index of the core of an optical fibre. These periodic variations are created by using powerful ultraviolet radiation (holographic method). Fig. 1 shows the internal structure of an optical fibre with an FBG written in it.

In a single mode optical fibre, light travels in the fundamental mode along the axis of the core of the fibre. When light passes through an FBG, Fresnel reflections take place due to the variations in refractive index of the fibre. This is called coherent reflection. If the criterion for constructive interference is met, then the incident light satisfies the Bragg condition is given by [1].

$$\lambda_B = 2n\Lambda \quad (1)$$

where λ_B is the Bragg wavelength, n is the effective refractive index of the FBG and Λ is the grating period. When the Bragg condition is satisfied, reflections from each successive period will be in phase. Light that does not satisfy the Bragg condition passes through the FBG as if it were of uniform refractive index n (Fig. 1).

3. Strain measurement using FBG sensors

When an FBG is strained, the Bragg wavelength, λ_B changes due to both the change in grating pitch, Λ (due to the simple elastic elongation) and due to the photoelasticity-induced change of the refractive index. The relative change in Bragg wavelength is given by [2]

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - \rho_e)\varepsilon \quad (2)$$

where ε is the longitudinal strain experienced by the optical fibre at the FBG location and ρ_e is the effective photo-elastic constant of the fibre core material

$$\rho_e = \frac{n^2}{2}[p_{12} - \nu(p_{11} + p_{12})] \quad (3)$$

where p_{ij} are the silica photo-elastic tensor components and ν is the Poisson's ratio.

For an FBG of central wavelength of 1550 nm, typical strain sensitivity $\Delta\lambda_B/\Delta\varepsilon$ = 1.2 pm/microstrain [5].

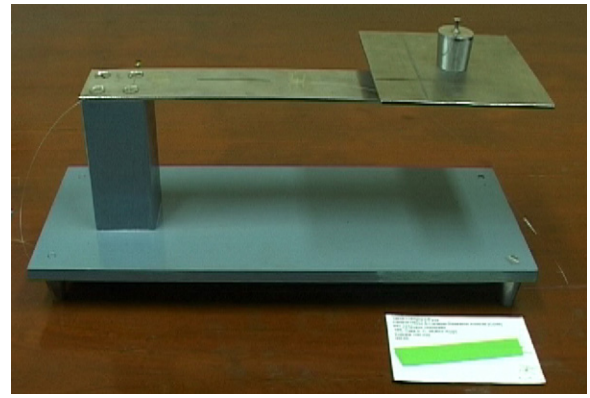

Fig. 2. A stainless steel cantilever structure has been fabricated in-house and FBGs are placed on it for strain calibration.

The Bragg wavelength λ_B is also susceptible to temperature changes. The change in wavelength is due to the combined effect of the thermal expansion of the core material and the thermo-optic behaviour that induces a change in the refractive index of the fibre.

The relative change in the Bragg wavelength due to temperature change is given by

$$\frac{\Delta\lambda_B}{\lambda_B} = (\alpha + \xi)\Delta T \quad (4)$$

where ΔT is the change in temperature experienced at the FBG location, α is the thermal expansion and ξ is the thermo-optical coefficient.

For an FBG of central wavelength of 1550 nm, typical temperature sensitivity $\Delta\lambda_B/\Delta T$ = 13 pm/°C [5]. However, the strain and temperature sensitivities of FBG sensors depend on the type of fibres as well [6].

3.1. Experimental setup for FBG based strain measurement

Although the application of bare FBG on real structural application is not advisable due to fragility of the silica fibre, a few tests have been performed in the laboratory with bare FBG on a stainless steel (Fig. 2) structure fabricated in-house. However these tests are essential to ascertain the strain-opto coefficient of the bare fibre. FBGs are placed on the axis of the cantilever for strain calibration as shown in Fig. 2.

The optical-setup is presented in Fig. 3. A tuneable fibre laser source emitting (1520–1570 nm) with a maximum power of 2 mW is used for interrogation of 80–90% reflectivity FBG elements centered at 1551 nm. The laser, illuminated with a single-mode fibre pig-tail, is directly connected to the FBG via a 50:50 (3 dB) fused coupler (developed at CGCRI) which is also used to collect Bragg wavelength reflected by the grating. The reflection coming from

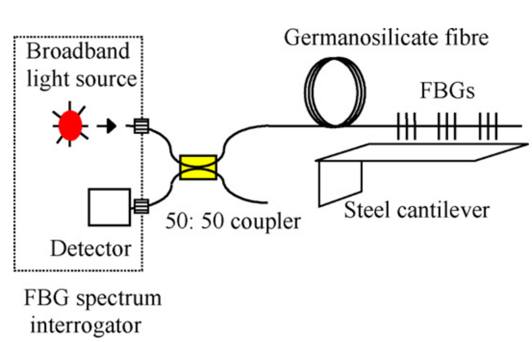

Fig. 3. Schematic diagram of experimental set-up and steel cantilever.