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Pressure Sensitivity Analysis of Fiber Bragg Grating Sensors

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Abstract

Recent development in fiber optic sensing technology has mainly focused on discrete sensing, particularly, sensing systems with potential multiplexing and multi-parameter capabilities. Bragg grating fiber optic sensors have emerged as the non-disputed champion for multiplexing and simultaneous multi-parameter sensing for emerging high value structural components, advanced processing and manufacturing capabilities and increased critical infrastructure resilience applications. Although the number of potential applications for this sensing technology is large and spans the domains of medicine, manufacturing, aerospace, and public safety; critical issues such as fatigue life, sensitivity, accuracy, embeddability, material/sensor interface integrity, and universal demodulation systems still need to be addressed.

The purpose of this paper is to primarily evaluate Commercial-Of-The-Shelf (COTS) Fiber Bragg Grating (FBG) sensors' sensitivity to pressure, often neglected in several applications. The COTS fiber sensitivity to pressure is further evaluated for two types of coatings (Polyimide and Acrylate), and different arrangements (arrayed and single).

Keywords: fiber optic sensors, fiber Bragg Gratings, strain, pressure, pressure sensitivity.

1.0 Introduction

With the emergence of multi-functional self-sensing and repair structures, and morphing concepts, several sensing technologies, such as polymer-based, piezoelectric-based, Nitinol-fiber based sensors along with micro, nano, and fiber optic sensors, have emerged as strong candidates for the development of such emerging concepts. Of these novel sensors, fiber optic sensors are considered to be the leading contender in forming the nervous system of functional structures due to their numerous advantages [1-2].

Since their introduction in the mid-seventies, a variety of fiber optic sensor configurations have been developed for the measurement of shape, deformation, temperature, pressure, humidity, chemical concentrations, etc. [3-8]. Variations of these parameters alter the refractive index and the geometric properties of the optical fiber (known as waveguide), which in turn perturbs the intensity, phase, or polarization of the propagating light wave. The perturbation of the light wave provides the sensor output through simple to complex demodulation techniques [9-10]. From a practical point of view, these optical fiber sensors, which can also be categorized as intrinsic or extrinsic [11], can be divided into two broad classes, namely short- and long-gauge length optical fiber sensors. Short-gauge length (point or discrete) optical fiber sensors, which are comparable to conventional sensors (*i.e.*, resistance strain gauges, thermocouples), have gauge length on the order of few millimeters, and typically measure physical parameters over distances less than 20 mm. Long-gauge length (distributed or distributed-effect) optical fiber

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sensors have gauge length ranging from few centimeters to hundreds of meters, and typically measure physical parameters over distances of few centimeters to few meters (0.05 m to 5 m). The advantages of the single-ended discrete sensors include their reduced intrusiveness in embedded configurations, reduced number of the ingress/egress locations, and their placement flexibility in hard to reach areas. The advantage of distributed sensors is their ability to span larger spatial domain but with the drawback of limited spatial resolution (1 cm at best) that is at times irrelevant.

Recent development in fiber optic sensing technology has mainly focused on discrete sensing, particularly sensing systems with potential multiplexing and multi-parameter sensing capabilities. Bragg grating (Long Period Gratings (LPG), Tilted Fiber Bragg Gratings (TFBG)) fiber optic sensors [12] have emerged as the non-disputed champion in multiplexing and potential simultaneous multi-parameter sensing [13-14]. The single-ended, highly multiplexed (up to hundreds of discrete sensors on a single fiber) sensors are envisaged to be the primary sensory system for emerging high value structural components, advanced processing and manufacturing capabilities and increased critical infrastructure resilience applications, where conventional sensing technology is not suitable. Although the number of potential applications for this sensing technology is large and spans the domains of medicine, manufacturing, aerospace, and public safety, critical issues such as fatigue life, sensitivity, accuracy, embeddability, material/sensor interface integrity, and universal demodulation systems still need to be addressed.

The purpose of this paper is to primarily evaluate Commercial-Of-The-Shelf (COTS) fiber Bragg Grating sensors' sensitivity to pressure, often neglected in several applications. The COTS fiber sensitivity to pressure is further evaluated for two types of coatings (Polyimide and Acrylate) and different arrangements (arrayed and single.)

2.0 Fiber Bragg Gratings – The Approach

In a Fiber Bragg Grating (FBG) sensor, the periodically modulated refractive gratings (or Bragg gratings) inscribed inside the fiber, by a pair of strong ultraviolet beams of light or employing a mask, act as a wavelength selective channel where the successive semi-reflective gratings reflect and transmit specific wavelengths of light depending on their refractive indices.

As depicted in Figure 1, the grating partially reflects the incident light, traveling along the core of the fiber, to produce a narrow spectral band. The transmitted light is exploited to interrogate numerous gratings further down the core of the fiber, if multi-gratings with different wavelengths are inscribed. The wavelength of the reflected signal, λ_o (Bragg wavelength), is directly related to the grating pitch (distance between gratings, Λ) defined by the Bragg condition,

$$\lambda_o = 2\, n_{eff} \Lambda \qquad (1)$$

External disturbances, such as strain, temperature, pressure, are known to affect the grating period and the effective core refractive index (n_{eff}), hence the reflected wavelength as follows,

$$(\lambda-\lambda_o)/\lambda_0 = (1-p_e)\varepsilon + (\alpha+\xi)\Delta T + \eta\Delta P; \quad p_e = n_{eff}^{2}/2\{p_{12}-\nu\,(p_{11}+p_{12})\} \qquad (2)$$

where p_e denotes the effective strain-optic or photo-elastic coefficient, α the thermal expansion coefficient, ξ the thermo-optic coefficient and η the effective Young's modulus coefficient of the fiber material. Variations of ε, ΔT and ΔP denote strain, temperature and pressure changes, respectively [12]. For this investigation, sensors characteristics (COTS sensors) are determined, computed and presented in Table 1.

Variations in optical fibers properties result in variation of the computed values, as illustrated in Table 2. Fiber properties are not provided in the table and the reader is encouraged to consult the references provided [16-18]. It is noted that variations in the effective Young's modulus coefficient, sensor gauge factor, and the thermal expansion and thermo-optic coefficients are found to be of 244%, 0.2%, and 25%; respectively.

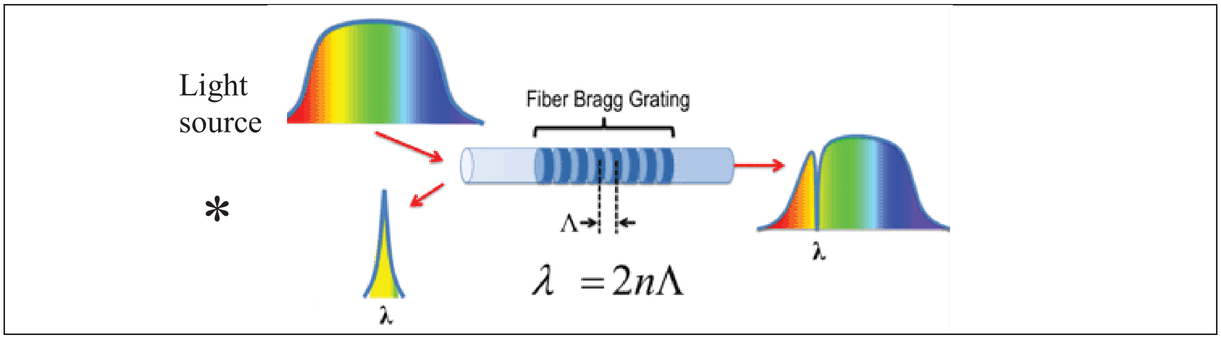

Figure 1. Fiber Bragg Grating sensing concept [after 15]

Table 1. Characteristics of COTS optical fiber sensors

	Property	**Symbol [Unit]**	**Values (COTS)**
Mechanical Properties of Fiber	Young's Modulus	E [MPa] E [PSI]	70,000 $1.1x10^7$
	Poisson Ratio	μ	0.17
Strain Optic Properties for Fused Silica	Strain optic coefficients	p_{11}	0.126
		p_{12}	0.27
	Effective refractive index of fiber core	n	1.46
	Thermal expansion coefficient of the fiber core	α [/°C]	$0.55x10^{-6}$
	Thermo-optic coefficient of fiber core	ξ [/°C]	$9.1x10^{-6}$
Computed Values	Effective Young's Modulus Coefficient	η [/MPa]	$-2.73596x10^{-6}$
	Sensor Gauge Factor	$(1-p_e)$	0.782
	$(\alpha + \xi)$	[/°C]	$9.65x10^{-6}$

Table 2. Sample Variation in Fiber optic Characteristics

	Property	Symbol [Unit]	Typical Values		
			[16]	[17]	[18]
Computed Values	Effective Young's Modulus Coefficient	η [/MPa]	$-5.18\text{x}10^{-6}$	--	--
	Sensor Gauge Factor	$(1-p_e)$	0.784	--	0.787
	$(\alpha + \xi)$	[/°C]	$9.4\text{x}10^{-6}$	$9.0\text{x}10^{-6}$	$9.15\text{x}10^{-6}$

3.0 Theoretical Approach and Analysis

Reekie *et al.* [16] outlined the results of various laboratory experiments that they conducted for monitoring ultrahigh hydrostatic pressure (up to 70 MPa). From the acquired data, a graph was reproduced (ignoring the effect of temperature and strain in Eq. (2)) relating pressure and wavelength change observed on a fiber optic pressure sensor. Figure 2 illustrates such results alongside the current results using COTS sensors (from Table 1). It is noted that there is a significant contrast between the results obtained. As the publication itself put it, the values differ by a large amount because of the uncertainty involved in the accuracy of the fiber parameter values (E, p_{11}, p_{12} etc.)

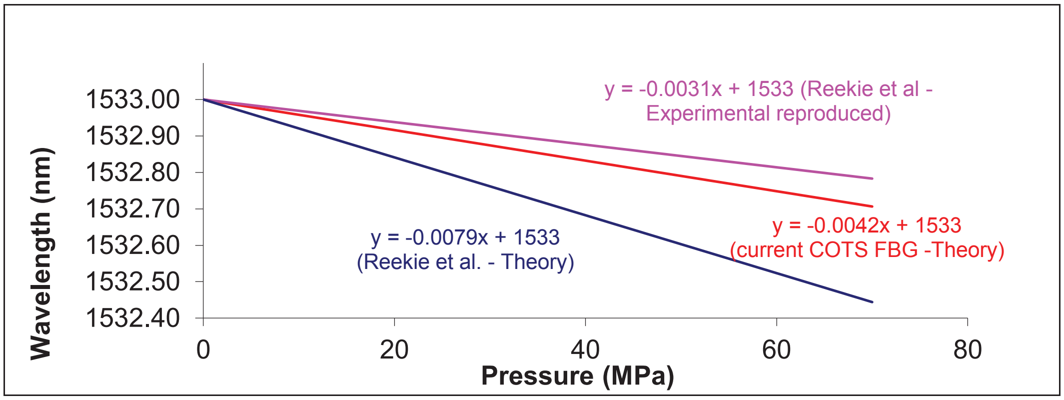

Figure 2. Sensitivity of fiber optic sensor to pressure

To validate the accuracy of the effective Young's modulus (η) the following equation (3) is used where the coefficient η (/°MPa) represents the slope of the wavelength-Pressure relationship [16].

$$\frac{\Delta\lambda o}{\lambda o\Delta P}=\eta=-\frac{(1-2\mu)}{E}+\frac{n^{2}}{2E}(1-2\mu)(2p_{12}+p_{11}) \tag{3}$$

Where the λ_o is the Bragg wavelength, $\Delta\lambda_o$ is the change in Bragg wavelength, ΔP is the change in pressure, μ is Poisson's ratio, E is the Young's modulus, n is the refractive index of the fiber core and $p_{12,}$ p_{11} signify the strain-optic coefficients of the fiber material. As illustrated in Table 3, for a Bragg wavelength of 1533 nm, the computed (COTS) η varied from the computed, experimental, and predicted values provided in [16], by 244%, 76%, and 0.4%, respectively. Additionally, when varying the Bragg wavelength from 1533 nm, 1539 nm and 1544 nm, no changes were observed in the computed effective Young's modulus (η), as illustrated in Table 4. Our earlier work [12, 19] investigated the variations of fiber coating thickness and type on the strain transfer and sensor sensitivity to applied loads.

Table 3. Effective Young's modulus coefficient (λ_o=1533 nm)

	Predicted [16]	Experimental [16]	Computed [16]	Computed (COTS)
η (/MPa)	$-5.18\text{x}10^{-6}$	$-1.98\text{x}10^{-6}$	$-2.74\text{x}10^{-6}$	$-2.73596\text{x}10^{-6}$

Table 4. Variation of effective Young's modulus (η) to wavelength variation

	λ_{o1} = 1539.021 nm	λ_{o2}=1544.75 nm
η (/MPa)	$-2.73596\text{x}10^{-6}$	$-2.73596\text{x}10^{-6}$

In the analysis that follows the pressure-wavelength relationship for the 1539 nm and 1544 nm FBGs is explored while assuming that the parameter values of Young's modulus, strain-optic coefficients, poison's ratio etc. are equal for both Acrylate and Polyimide coated sensors.

4.0 Experimental Results and Analysis

Even though several FBG demodulation systems exist [20-22], the one that was adopted (Figure 3) for this particular work consists of the following components: broadband light source, multi-wavelength meter, COTS FBG sensors (Acrylate and Polymer coated), circulator, data acquisition (DAQ) device, a custom software program, power supply, pressure transducer, pressure pump, adapter board and a USB capable thermocouple. The experimental analysis consists of determining the effective Young's modulus (η) for two types of fiber sensors (Acrylate and Polyimide coated) with Bragg wavelengths as shown in Table 5. The first series of experiments were conducted employing the single Acrylate coated grating. A total of three trials were completed with pressures induced as high as 60 MPa. For each of those trials the effective Young's modulus (η) is obtained using:

$$\frac{\lambda - \lambda o}{\lambda o} = \eta \Delta P \tag{4}$$

The average of the three experimentally obtained effective Young's modulus is presented in Table 6. This average varied by 13.3% from the theoretical value of $-2.73596\text{x}10^{-6}$/MPa. Figure 4 illustrates a typical experimental result for wavelength-pressure relationship for the Type A sensor (1539 nm).

Figure 3. Experimental setup for pressure measurement

Table 5. Characteristic information on the different type of sensors

Sensor	Part # (Type)	Description	Coating Material	Center Wavelength (nm)
1	Type A	Single Grating	Acrylate	1539.021
2	Type B	Two Arrayed (not collocated) Gratings	Polyimide	1539.021/1544.75

Table 6. Effective Young's modulus for Type A (1539 nm) single Acrylate coated grating

λ_o=1539.021 nm	η (/MPa)
Theory	-2.736x10^{-6}
Average experimental value	-2.869x10^{-6}

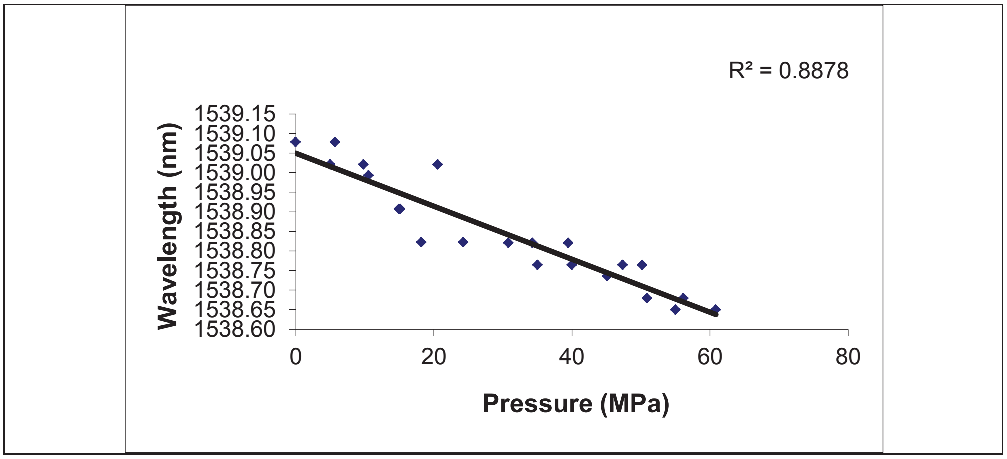

Figure 4. Typical experimental Wavelength-Pressure relationship for the Type A sensor (Trial 1)

Additionally, a second set of three experimental trials using a set of two arrayed Polyimide coated grating sensors (Type B), with Bragg wavelengths of 1539 nm and 1544 nm, was conducted. The pressure-wavelength data was collected and analyzed for both gratings. The effective Young's modulus for each trail was experimentally obtained and the average was presented in Table 7 for λ_o=1539 nm. This average varied by 106.3% from the theoretical value of -2.73596x10^{-6}/MPa.

Table 7. Effective Young's modulus for Type B (1539.021 nm) two Polyimide coated arrayed gratings

λ_o=1539.021 nm	η (/MPa)
Theory	-2.736x10^{-6}
Average experimental value	-3.799x10^{-6}

It is observed that variation in the pressure sensitivities for the two arrayed Polyimide coated grating sensors (Type B) is insignificant, as both gratings with wavelengths of 1539 nm and 1544 nm, experienced the same experimental conditions.

5.0 Discussion and Analysis

In this study, the analysis focused on verifying the results presented by Reekie *et al.* [16] and on evaluating COTS fiber Bragg Grating sensors' sensitivity to pressure, that is often neglected. The COTS fiber sensitivity to pressure is evaluated for Polyimide and Acrylate coated gratings in single and arrayed configurations with different Bragg wavelengths. It is determined that the results presented by Reekie *et al.* [16] are erroneous, as they 244% (theoretically) and 76% (experimentally) sensitivity variation was observed. Additionally, for Acrylate (Type A) coated grating, the effective Young's modulus (η) was determined to be -2.869 x10^{-6} /MPa and varied by 13.3% from the theoretical value of -2.73596x10^{-6}/MPa. When arrayed Polyimide coated grating sensors (Type B) was used, the effective Young's modulus was found to be -3.79917 x10^{-6}, which is 106.3% variation from the theoretical value. The variation could be attributed to the variation in coatings used for both sensors type, since this is the only significant difference between the inherent compositions of the sensors. The effective Young's modulus difference observed for the 1539 nm gratings on the two employed sensors can be summarized by

$$\eta_{Theory} > \eta_{Acrylate} > \eta_{Polymide}$$

Research has shown that the typical compressive yield strength of Polyimide is around 150 MPa whereas that for Acrylate it is 95 MPa [23]. This means that the Acrylate coated sensor is less sensitive to compressive loads than that of Polyimide coated Gratings. Additionally, it should be identified that the Acrylate coated sensor has a 250 μm diameter; whereas Polyimide coated sensor had a diameter of 140 μm. This variation in fiber diameter could affect the fiber Young's modulus; hence the effective Young's modulus (η). Indeed, the theoretical value of Young's (Elastic) modulus (70 GPa), known also as effective Young's modulus for the whole fiber (core, cladding, coating inclusive) was used for both the Polyimide and Acrylate coated sensors. Investigation revealed that in polymers, the tensile modulus and compressive modulus can be close or may vary widely by up to 50% or more, depending on resin type, reinforcing agents, and processing methods. The tensile and compressive moduli are often very close for metals [24]. In the face of the identified uncertainties and assumptions, one can argue that the experimentally obtained η is within the experimental uncertainty, nonetheless cannot be ignored.

6.0 Conclusion

In the presented analysis, it can be deduced that fiber Bragg grating sensors are sensitive to pressure variations. Sensitivity was found to be higher for Polyimide coated Bragg gratings than for Acrylate ones. Additionally, no change in sensitivity was observed for different Bragg grating wavelengths. Furthermore, results presented by [16] were found to be erroneous.

It is recommended that in interpreting the presented results, the reader is advised to take the following factors into consideration: variations in the sensor coating's elastic modulus (overall Young's modulus), coating and fiber core thickness/diameter, and the center (Bragg) wavelength separation in the arrayed dual gratings configuration.

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