Experimental investigation and study of spectral response of fiber Bragg gratings under transverse load conditions

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ABSTRACT
Fiber Bragg Grating sensor technology has been conventionally used to sense axial strain and temperature. However Fiber Bragg Gratings (FBG) are capable of monitoring transverse stress as well. In this paper we present the results of experimental investigations and theoretical analysis conducted on FBG with transverse load. We also propose a new method to discriminate the effect of transverse pressure and temperature on FBG.

Keywords: Fiber Bragg gratings, Birefringence, Transverse pressure, Temperature and Polarization.

1.INTRODUCTION
Fiber Bragg gratings are fast becoming a technological choice for a wide range of optical sensing techniques. Being a wavelength selective filter, FBG can be used as an effective point sensor for measuring strain, temperature and pressure. A Bragg grating consists of periodic perturbations in the index of refraction along the length of the optical fiber. The grating reflects a narrow band peak depending on grating period and effective refractive index of the mode of the fiber. Thus changes in the refractive index and grating period due to tension and compression will change the grating spacing and the wavelength of reflected light. Quantitative strain measurements can be made by measuring the shift in the central wavelength of the reflected peak.

Apart from having the advantage of conventional optical sensors, such as immunity to electromagnetic interference, compactness and flexibility, FBG sensors offer additional features such as high density multiplexing and multiparameter sensing. However like other fiber sensors, an FBG based sensor, responds simultaneously to several physical parameters. For the development of a practical sensor, special measures must be taken to extract the signal that corresponds to the parameter to be measured. Separation of various physical effects is therefore an important issue in the development of FBG based sensors. In oil and gas industry, FBG sensors have potential significant advantages compared to conventional sensor systems particularly for down hole permanent monitoring applications. In such applications transverse pressure measurements are of prime importance.

When a FBG is subjected to transverse load. Stress induced birefringence in the fiber causes a split in the Bragg peak spectrum. Birefringence originates from what is called as geometrical anisotropy and residual internal stress. Birefringence is the condition where two orthogonal components have different indices of refraction. In this paper we present the results of experimental investigations and theoretical analysis conducted on FBG with transverse load. We have observed in our experiments that the wavelength shifts of both peaks have a different sensitivities to pressure and temperature. The reflected peak due to x-polarization has a higher sensitivity to both parameters when compared to the reflected peak due to y-polarization. This differential sensitivity of both peaks can be used in a matrix equation to determine the individual parameters.

2.THEORY

2.1 Theory of Fiber Bragg gratings
A Bragg grating consists of periodic perturbation in the index of refraction along the length of the fiber. Two important parameters characterize the FBG. The effective refractive index and the period of the grating. The Bragg wavelength \( \lambda_B \) is given by the condition,

\[
\lambda_B = 2n_{\text{eff,0}}\Lambda
\]

where \( n_{\text{eff,0}} \) is the effective refractive index at free space wavelength and \( \Lambda \) is the spacing between the grating lines.
When a FBG is subjected to transverse pressure 'P', the Bragg reflection wavelength shifts. The change in Bragg wavelength is given by,

\[ d\lambda_B = \left[ 2\Lambda_B \frac{\partial n_{\text{eff}}}{\partial P} \right]_{T = C^0} + 2n_{\text{eff,0}} \frac{\partial \Lambda_B}{\partial P} \left[ T = C^0 \right] dP + \left[ 2\Lambda \frac{\partial n_{\text{eff}}}{\partial T} \right]_{P = C^0} + 2n_{\text{eff,0}} \frac{\partial \Lambda_B}{\partial T} \left[ T = C^0 \right] dT \] (2)

where T is the Temperature.

### 2.2 Refractive index changes induced by external transverse load

When transverse load is applied to circular core FBG, the crosssection becomes elliptical. It is compressed in the direction of force (Y-axis) and it is out in tension in the orthogonal direction (X-axis). In the compressed direction index of refraction increases and in orthogonal direction index of refraction decreases as shown in figure 1.

As a result, two plane polarized waves will propagate, with the principle axes of polarization parallel and perpendicular to the direction of applied load. The induced birefringence 'B' of the light propagating along z-axis is given by,

\[ B = \left| n_\parallel - n_\perp \right| \]

where \( n_\parallel \) and \( n_\perp \) are the refractive indices parallel and perpendicular respectively to the direction of applied load, \( n_{\text{eff,0}} \) is the initial effective index of refraction before loading.

\[ B = B_0 + \left| \Delta n_\parallel - \Delta n_\perp \right| \]

where \( B_0 \) is the inherent birefringence before loading, \( \Delta n_\parallel \) and \( \Delta n_\perp \) are the refractive index changes for x and y polarizations respectively due to applied loads. We assume birefringence \( (B_0) \) induced by manufacturing and writing process to be very small compared to the birefringence induced by applied load. Therefore induced birefringence is

\[ B = \left| \frac{\Delta n_\parallel - \Delta n_\perp}{n_{\text{eff,0}}} \right| \] (5)

The refractive index changes of the FBG are derived by photo-elasticity theory. The refractive index changes at any point M (x, y, z) of the FBG in the grating zone, developed to the first order are given by
\[
\Delta \left( \frac{I}{n_{\text{eff}}^2} \right)_x = -2 \left( \frac{\Delta n_{\text{eff}}}{n_{\text{eff},0}} \right)_x^2 = p_{12} \varepsilon_x + p_{11} \left[ \varepsilon_y + \varepsilon_z \right]
\]

(6)

\[
\Delta \left( \frac{I}{n_{\text{eff}}^2} \right)_y = -2 \left( \frac{\Delta n_{\text{eff}}}{n_{\text{eff},0}} \right)_y^2 = p_{11} \varepsilon_y + p_{12} \left[ \varepsilon_x + \varepsilon_z \right]
\]

(7)

where \( p_{11} (0.121) \) and \( p_{12} (0.27) \) are photo-elastic coefficients of the undisturbed optical fiber; \( \varepsilon_x, \varepsilon_y \) and \( \varepsilon_z \) are the strain components at point \( M(x, y, z) \) in the FBG in \( x, y \) and \( z \) directions.

Using stress - strain relationship, effective refractive index changes are as follows, for \( x \) polarization,

\[
\left( \Delta n_{\text{eff}} \right)_x = -\left( \frac{n_{\text{eff},0}}{2E} \right)^3 \left\{ (p_{11} - 2\nu p_{12}) \sigma_x + [(1 - \nu)p_{12} - \nu p_{11}] \times [\sigma_y + \sigma_z] \right\}
\]

(8)

for \( y \) polarization,

\[
\left( \Delta n_{\text{eff}} \right)_y = -\left( \frac{n_{\text{eff},0}}{2E} \right)^3 \left\{ (p_{11} - 2\nu p_{12}) \sigma_y + [(1 - \nu)p_{12} - \nu p_{11}] \times [\sigma_x + \sigma_z] \right\}
\]

(9)

where \( E \) is the Young’s modulus of silica fiber (74.52 GPa) \( \nu \) is the Poisons coefficient of optical fiber (0.17) and \( \sigma_x \) and \( \sigma_y \) are the stress components in \( x \) and \( y \) directions.

These stress components for a given Transverse force \( F \), length of grating \( l \) and diameter of fiber \( D \) are given by

\[
\sigma_x = \frac{2F}{\pi D}; \sigma_y = \frac{-6F}{\pi D}.
\]

\[ (\Delta \lambda_B)_x = -\frac{\Lambda_B(\text{eff},0)}{E} \left\{ (p_{11} - 2\nu p_{12}) \sigma_x + [(1 - \nu)p_{12} - \nu p_{11}] \times [\sigma_y + \sigma_z] \right\} + 2\frac{n_{\text{eff},0} \Lambda_B(\text{eff},0)}{E} \times [\sigma_z - \nu [\sigma_x + \sigma_y]]
\]

(10)

\[ (\Delta \lambda_B)_y = -\frac{\Lambda_B(\text{eff},0)}{E} \left\{ (p_{11} - 2\nu p_{12}) \sigma_y + [(1 - \nu)p_{12} - \nu p_{11}] \times [\sigma_x + \sigma_z] \right\} + 2\frac{n_{\text{eff},0} \Lambda_B(\text{eff},0)}{E} \times [\sigma_z - \nu [\sigma_x + \sigma_y]]
\]

(11)

Figure 2: Plot showing variation of refractive index along the length of the fiber for transverse load.

Refractive index changes for \( x \) polarization are higher than for \( y \) polarization because of mechanical and photoelastic properties of optical fiber material (\( p_{11} < p_{12} \)).

Bragg reflection wavelength changes at any point of the disturbed FBG is given by,
The second terms of the above equation are identical and correspond to Bragg reflection wavelength changes of the FBG induced by longitudinal strain. In the case of plane stress as a result of pure transverse load $\sigma_z = 0$, therefore the second terms are neglected.

### 2.3 Effects of Temperature on transverse loaded FBG

The thermal response on the two linearly polarized $x$ and $y$ modes arises due to inherent thermal expansion of the fiber material and the temperature dependence of the refractive index. The shift in the Bragg wavelength with temperature can be expressed using,

\[
(\Delta \lambda_B)_{x,T} = 2\left\{\left(\frac{\Delta n_{\text{eff},x}}{\Delta T}\right)\Lambda_g + \left(\frac{\Delta \Lambda_g}{\Delta T}\right) n_{\text{eff},x}\right\} 
\]

\[
(\Delta \lambda_B)_{y,T} = 2\left\{\left(\frac{\Delta n_{\text{eff},y}}{\Delta T}\right)\Lambda_g + \left(\frac{\Delta \Lambda_g}{\Delta T}\right) n_{\text{eff},y}\right\} 
\]

But the sensitivity of stress induced Birefringence due to change of temperature is given by\textsuperscript{5}

\[
B = -CA_T\Delta T \tag{14}
\]

where $C$ is the stress optic coefficient, $\Delta T$ is the change in the temperature, $A_T$ is the sensitivity of birefringence due change in temperature and is given by,

\[
A_T = -\frac{E\Delta \sigma B}{2(1-\nu)} \tag{15}
\]

From the above equation, it is clear that the temperature dependence of stress response of FBG is mainly characterized by Young's modulus of fiber material. The stress sensitivity decreases linearly by $1.22 \times 10^{-4}$ K\textsuperscript{-1} over the temperature range -38 °C to 110 °C. This is nearly identical to increase of Young's modulus of fused silica over this range, implying that it is predominantly Young's modulus that defines and characterizes thermal dependence of Birefringence.

Equation (14) can be rewritten as\textsuperscript{6}

\[
\frac{\Delta n_{\text{eff},x}}{\Delta T} = \frac{\Delta n_{\text{eff},y}}{\Delta T} + CA_T \tag{16}
\]

and on substituting equation (15) in equation (12) and (13) gives,

\[
(\Delta \lambda_B)_{x,T} = 2\left\{\left(\frac{\Delta n_{\text{eff},y}}{\Delta T} + CA_T\right)\Lambda_g + \left(\frac{\Delta \Lambda_g}{\Delta T}\right) n_{\text{eff},x}\right\} 
\]

\[
(\Delta \lambda_B)_{y,T} = 2\left\{\left(\frac{\Delta n_{\text{eff},y}}{\Delta T}\right)\Lambda_g + \left(\frac{\Delta \Lambda_g}{\Delta T}\right) n_{\text{eff},y}\right\} 
\]

### 3.EXPERIMENTAL INVESTIGATION

Light emitted from a broadband band light emitting diode with an inbuilt circulator, is launched into a FBG. The reflected spectrum from the FBG was observed on Optical Spectrum Analyzer (OSA) with 0.1nm resolution as shown in the figure 3(a). A special compression device as shown in the figure 3(b) was designed and manufactured, where the compression area was a highly polished square steel slab of 30 mm side. A universal joint was installed between the top plate and handle, at the end of which a force was applied, in order to minimize uneven distribution of load on the gratings. A FBG of length 10 mm was placed on the compression platform along with a balancing reference fiber of identical physical characteristics in order to ensure even distribution of load.

When the fiber is compressed laterally the contact area between the fiber and plate will be line only at very loads. As load increases the contact area also increases. The contact length ‘$2a$’ can be expressed by the relation’.
\[2a = 4 \left[ \frac{PR \left( \left( 1 - v_2^2 \right) E_1 + \left( 1 - v_1^2 \right) E_2 \right)}{\pi d \left( E_1 E_2 \right)} \right]^{1/2} \]  

(19)

The temperature was varied by immersing the setup in a water bath whose temperature was controlled by an immersed heater.

4. RESULTS AND DISCUSSION

It was experimentally observed that complex changes occur in reflected spectrum under transverse loading. As load varies the reflected Bragg shifts in wavelength, this is due to coupling of energy from the two forward propagating linear modes to the corresponding backward propagating modes. But it was reported by Sakai \(^8\) that there will also be a cross coupling between the two linear polarized modes under transverse loading which results in energy redistribution between the two reflected peaks. The reflection spectrum of the FBG under transverse loading before and after spectral split is shown in figure (4).

From figure 5, it is observed experimentally that peak 1 has a wavelength shift of 1.528 pm/MPa and peak 2 has a wavelength shift of 6.656 pm/MPa compared to theoretical values of 1.2 pm/MPa for peak 1 and 5.2 pm/MPa for peak 2. Likewise from figure 6, it is experimentally observed that peak 1 has a wavelength shift of 14 pm/\(^\circ\)C and peak 2 has wavelength shift of 20 pm/\(^\circ\)C compared to theoretical values of 12.89 pm/\(^\circ\)C for peak 1 and 18.5 pm/\(^\circ\)C for peak 2. The differential sensitivities of the split peaks to transverse pressure and temperature are used to discriminate the same. The relationship is given by,
where $\Delta P$ and $\Delta T$ are the changes in pressure and temperature. $k_{1p}, k_{2p}, k_{1T}, k_{2T}$ are pressure and temperature sensitivities. $\Delta \lambda_1$ and $\Delta \lambda_2$ are the changes in Bragg wavelength of peak 1 and peak 2 respectively. Our experimental pressure and temperature sensitivity values are $k_{1p} = 1.528$ pm/MPa, $k_{2p} = 6.656$ pm/MPa, $k_{1T} = 14$ pm/°C, $k_{2T} = 20$ pm/°C.

5. CONCLUSION

The spectral response of a FBG under transverse load conditions is found to have a two peak structure. The wavelength shifts of both peaks have a different sensitivity to pressure and temperature. Peak 2 (x-polarization) has a higher sensitivity to both parameters when compared to peak 1 (y-polarization). This differential sensitivity of split peaks to individual parameters has been used to discriminate to transverse pressure and temperature.

6. REFERENCES