Compensating Bragg Wavelength Drift due to Temperature and Pressure by Applying an Artificial Strain

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Abstract A novel technique is proposed to produce a stable Bragg wavelength at different environmental conditions including temperature and pressure effects. The present work is focused on eliminating the change in Bragg wavelength by applying an artificial strain.

Keywords: Fiber Bragg Grating (FBG), FBG thermal sensitivity, Bragg wavelength, ocean depth, pressure, strain.

1. Introduction

In today's fiber optic communication systems, fiber Bragg gratings are key components for wavelength division multiplexing (WDM) applications and dispersion compensation [1]. FBGs are short lengths of optical fibers that reflect a particular wavelength. They are made by laterally exposing the core of a single-mode fiber to a periodic pattern of intense ultraviolet light. The exposure produces a permanent increase in the refractive index of the fiber core, creating a fixed index modulation according to the exposure pattern. This fixed index modulation is called a grating [2]. At each periodic refraction change a small amount of light is reflected. All reflected light signals combine coherently to one large reflection at a particular wavelength when the grating period is approximately half the input light wavelength. This is referred to as the Bragg condition [3], and the wavelength at which this reflection occurs is called the Bragg wavelength. FBGs are sensitive to temperature, pressure and strain effects [2 and 3]. In this paper, one emphasizes on the stability of Bragg wavelength at different temperature and pressure by applying an artificial strain.

The following study provides a detailed description of how one can cancel the change in Bragg wavelength due to temperature, $\Delta\lambda_{BT}$, by applying a strain on the grating giving a change, $\Delta\lambda_{BS}$, in Bragg wavelength. Thus, adjusting this change to be equal and opposite to the change obtained by temperature, $\Delta\lambda_{BT}$, ($\Delta\lambda_{BT} = -\Delta\lambda_{BS}$), to achieve a constant central Bragg wavelength. However, in the fiber cables under seawater, an additional effect is included which is pressure. It changes the Bragg wavelength by the increment $\Delta\lambda_{BP}$. The use of an artificial strain compensates for both temperature and pressure effects; i.e. $\Delta\lambda_{BS} = -(\Delta\lambda_{BT} + \Delta\lambda_{BP})$, where $\Delta\lambda_{BS}$ is the change caused by the strain. Thus, one can get stable Bragg wavelength.

In Sec.2, the effect of temperature only (ranging from –50 to 150 ^{O}C) is investigated. While, the effect of strain on Bragg wavelength is studied in Sec.3. The effect of both temperature and pressure under seawater depth as low as 4000 m is illustrated in Sec.4. This is followed, in Secs.5 and 6, by a study for compensating the drift in Bragg wavelength using an applied strain. Finally, numerical results are illustrated in Sec.7.

The mathematical analysis is based on the assumption that the FBG has a uniform index modulation, its length is 2.5 cm and the fiber core diameter is 8.2 μm.

Quanntity	Symbol	Value
Bragg wavelength	λ_{Bo}	1550 nm
Room temperature	T_o	25 ^{o}C
Thermo optical coefficient	α_n	8.6×10^{-6} $^{o}C^{-1}$
Thermal expansion coefficient	α_Λ	0.55×10^{-6} $^{o}C^{-1}$
Effective refractive index	n_{eff}	1.482
Grating period	Λ	0.5229 μm
Effective strain-optic constant	P_e	0.22

Table 1 Constants used in the paper.

2. The FBG Thermal Sensitivity

The Bragg grating resonance, which is the central wavelength of back-reflected light from a uniform Bragg grating is given by [1]:

$$\lambda_{Bo} = 2\ \Lambda\ n_{eff}, \quad (1)$$

where Λ is the grating period and n_{eff} is the effective refractive index. The shift $\Delta\lambda_B$ in the Bragg central wavelength λ_B is dependent on temperature. The effective refractive index of refraction as well as the periodic spacing between the grating planes are also affected by temperature changes. Using Eq. (2), the shift in the Bragg grating central wavelength due to temperature changes is given by:

$$\Delta\lambda_{BT} = 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T_{FBG}, \quad (2)$$

where $\Delta T_{FBG}=(T_H - T_o)$, T_H is the heating temperature in degree ^oC. Equation (2) can also be written in the form:

$$\Delta\lambda_{BT} = \lambda_{Bo}(\alpha_\Lambda + \alpha_n)\ \Delta T_{FBG}, \quad (3)$$

where λ_{Bo} is the FBG Bragg wavelength at a reference temperature of T_o, $\alpha_\Lambda(= 1/\Lambda.\partial\Lambda/\partial T)$ is the thermal expansion coefficient and α_n (= $1/n_{eff}.\partial n_{eff}/\partial T$) is the FBG thermo-optical coefficient. The FBG thermal sensitivity S_{FBG} is defined as [2]:

$$S_{FBG}= \frac{\Delta\lambda_{BT}}{\Delta T_{FBG}} = \lambda_{Bo}(\alpha_\Lambda+\alpha_n). \quad (4)$$

Hence, the Bragg central wavelength can be defined as:

$$\lambda_B=\lambda_{Bo} + S_{FBG}\Delta T_{FBG}, \quad (5)$$

or

$$\lambda_B = \lambda_{Bo} + \Delta\lambda_{BT}. \quad (6)$$

Equation (6) is plotted in Fig. 1, showing linear characteristics. From Fig.1, one can note the linear relationship between Bragg wavelength and temperature, which shows that the Bragg wavelength λ_B increases with temperature at a slope of 0.013 nm/^{O}C. The Bragg wavelength was centered at 1550 nm at room temperature.

Based on Refs. [4 and 5], the grating period is studied with temperature. From α_Λ (= $1/\Lambda.\partial\Lambda/\partial T$), one can plot the relation between the grating period and temperature and the results are displayed in Fig. 2.

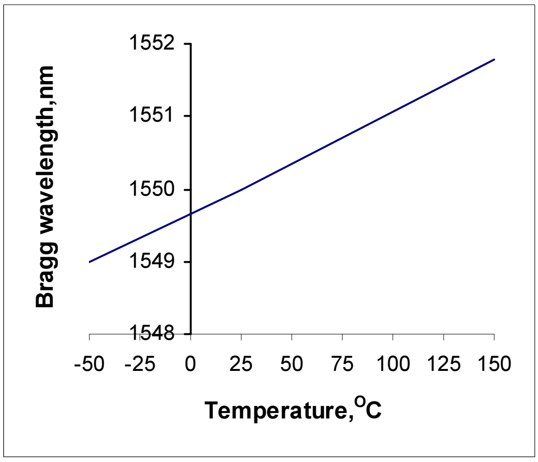

Fig.1 Bragg wavelength, λ_B, versus temperature.

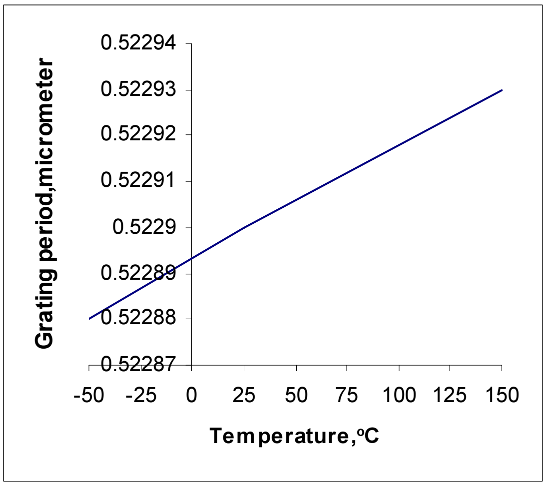

Fig. 2 Grating period versus temperature.

In Fig. 2, we see the linear relation between the grating period and temperature. We note that the grating period increases with temperature at a slope of 2.67×10^{-7} µm/^{O}C. At the same manner, we used α_n (= $1/n_{eff} . \partial n_{eff}/\partial T$) to plot the relation between the effective refractive index and temperature, which is also found linear at a slope of 1.6×10^{-5}/^{O}C, Fig. 3. As can be seen, the rate of effective refractive index change is higher than the period changes, and which is main contribution to the wavelength shift shown in Fig. 1.

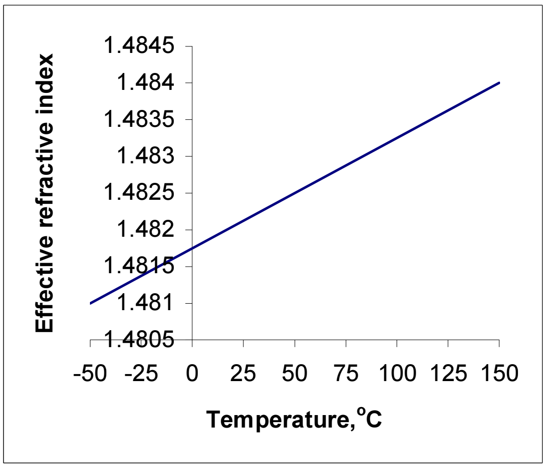

Fig. 3 FBG effective refractive index versus temperature.

3. Strain Sensitivity of FBG

The shift $\Delta\lambda_B$ in the Bragg central wavelength is also dependent on the change in the strain, which is given as [4]:

$$\Delta\lambda_{BS} = 2\left(\Lambda\frac{\partial n_{eff}}{\partial l} + n_{eff}\frac{\partial \Lambda}{\partial l}\right)\Delta l, \qquad (7)$$

where ΔL is change in length of FBG due to strain. The shift $\Delta\lambda_B$ is related to the strain applied to the grating and can be expressed by [4]:

$$\Delta\lambda_{BS} = \lambda_{Bo}.(1-P_e).\ \Delta\varepsilon_Z, \qquad (8)$$

where P_e is the effective strain-optic constant defined as [4]:

$$P_e = \frac{n_{eff}^2}{2}.\{P_{12} - \nu(P_{11} + P_{12})\}, \qquad (9)$$

where P_{11} and P_{12} are components of the strain-optic tensor, and ν is the Poisson's ratio. For a typical silica optical fiber P_{11}=0.153, P_{12}=0.273, ν=0.17, and n_{eff}=1.482. Consequently, P_e=0.22 [3 and 6].

Figure 4 illustrates the relationship between Bragg wavelength ($\lambda_B = \lambda_{Bo} + \Delta\lambda_{BS}$) and strain. The Bragg wavelength was centered at 1550 nm under zero strain. If the strain increases (tension) the Bragg wavelength increases linearly.

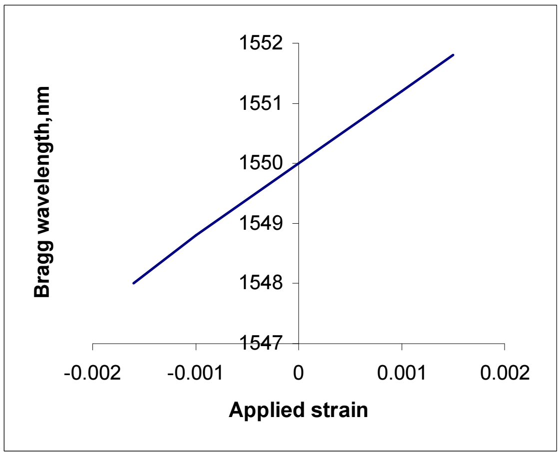

Fig. 4 Wavelength of fiber Bragg grating under applied strain.

4. Pressure and Temperature Effects on Bragg Wavelength

As we go deeper (under seawater), the pressure appears as a new parameter besides temperature. Most of the seawater is warm in the surfaces and cold at depth with an overall temperature rang 29 to –1.5 °C and the pressure increase with depth due to weight of the water above [6]. For a pressure change, the shift in the center Bragg wavelength is given by [4]:

$$\Delta\lambda_{BP} = \lambda_B.\left[\frac{-(1-2\nu)}{E} + \frac{n_{eff}^2}{2E}(1-2\nu)(2p_{12}+p_{11})\right].\Delta P, \qquad (10)$$

where E is the Young's modulus of the fiber (=72 Gpa). For a normal silica mode fiber, the Bragg wavelength 1550 nm, n_{eff} 1.482 and

$\Delta P = P_t - P_{atm}$,

$P_t = P_{atm} + P_{water}$,

$\Delta P = P_{atm} + P_{water} - P_{atm}$,

$$P_{water} = d \times \rho \times g, \qquad (11)$$

where d is the depth, ρ is the density of the overlying water column (= 1027.3 Kg/m^3) and g is acceleration of gravity.

Most of the ocean is warm in the surface and cold at depth with an overall temperature range of –1.5° to 29° C.

The ocean is divided into three layers based on temperature [7]:

1. Surface mixed layer, which is warm and uniform in temp (typically 0 to ~100 m).
2. Thermo cline where the temperature decrease is largest (100 m to ~1500 m).
3. Deep sea where temperature is cold and fairly uniform (1500 m – 4000 m).

Figure 5 shows an approximated relation between sea depth ranging from 1 to 4000 m and their corresponding temperatures at these depths. Figure 6 shows the relation between change in Bragg wavelength due to pressure, $\Delta\lambda_{BP}$, where the pressure is presented by the depth of the seawater. In Figure 7, the relation is displayed between the change in Bragg wavelength due to temperature $\Delta\lambda_{BT}$ and temperature from –1.5 to 29 °C.

The overall change in Bragg wavelength due to the effect of both the temperature and pressure is illustrated in Fig. 8. It is clear that for depths till 2000 m the overall change in Bragg wavelength is high and as we go deeper the change is smaller. This is due to the nonlinear relation between temperature and depth. This shows that the drift due to temperature is greater than that of pressure.

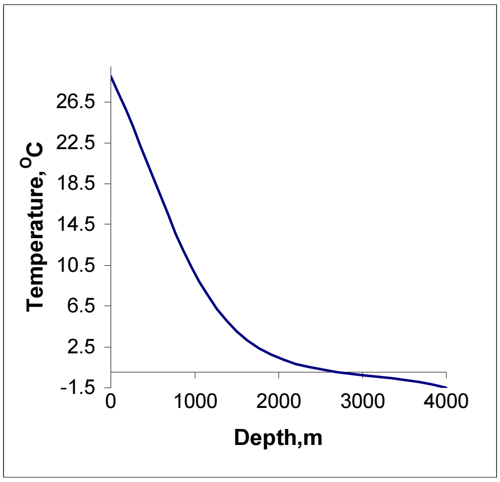

Fig. 5 Temperature versus depth.

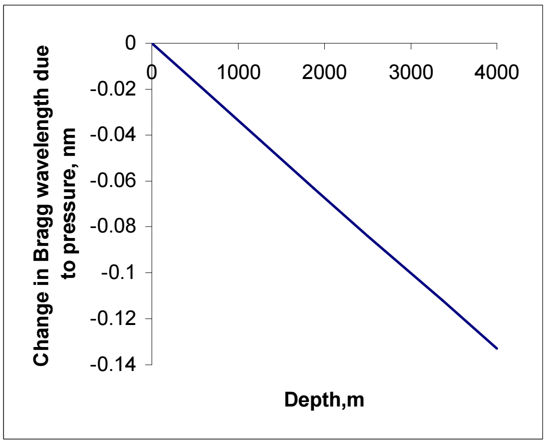

Fig. 6 Change in Bragg wavelength versus depth.

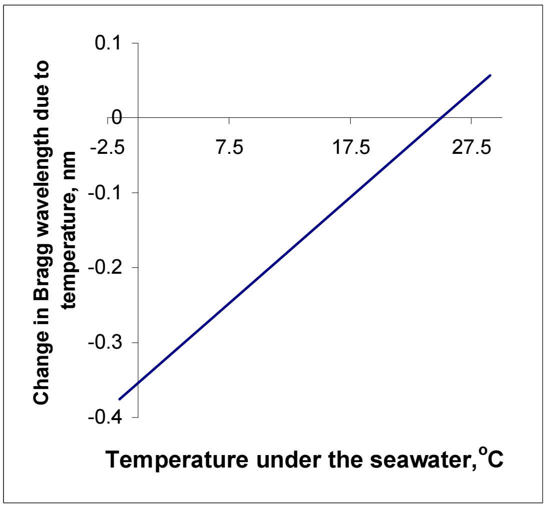

Fig. 7 Change in Bragg wavelength with temperature.

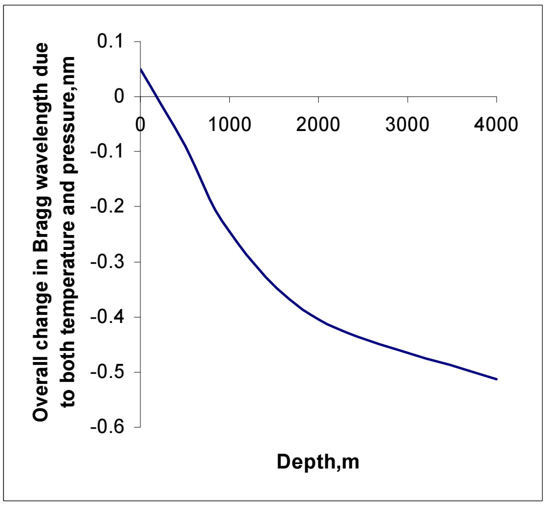

Fig. 8 Overall change in Bragg wavelength versus seawater depth.

5. Compensating Bragg Wavelength Drift due to Temperature.

The main purpose of our work is stabilizing Bragg wavelength. One can achieve this by applying a strain giving an opposite drift in Bragg wavelength that opposes the drift occurred due to temperature, pressure or both. The relation helping to achieve that is simply:

$$\Delta\lambda_{BS} = - [\ \Delta\lambda_{BT} + \ \Delta\lambda_{BP}]. \quad (11)$$

To cancel the drift in Bragg wavelength due to temperature using Eqs. (2) and (7), one can calculate the total shift in Bragg wavelength due to strain and temperature as following:

$$\Delta\lambda_B = 2\left(\Lambda\frac{\partial n_{eff}}{\partial l} + n_{eff}\frac{\partial\Lambda}{\partial l}\right)\Delta l + 2\left(\Lambda\frac{\partial n_{eff}}{\partial T} + n_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T_{FBG} \quad (12)$$

Substituting Eqs. (3) and (8) on the expression given in Eq. (12), the total shift of the FBG reflection wavelength can be written as:

$$\Delta\lambda_B = \Delta\lambda_{BS} + \Delta\lambda_{BT.} \quad (13)$$

$$\Delta\lambda_B = \lambda_{Bo}[(1-p_e)\Delta\varepsilon_z + (\alpha_\Lambda + \alpha_n)\Delta T_{FBG}]. \quad (14)$$

For a stable Bragg wavelength ($\Delta\lambda_B$=0), therefore

$$\Delta\lambda_{BS} = -\ \Delta\lambda_{\ BT}, \quad (15)$$

Equation (14) is now used to plot the effect of strain and temperature on the Bragg wavelength as shown in Fig. 9.

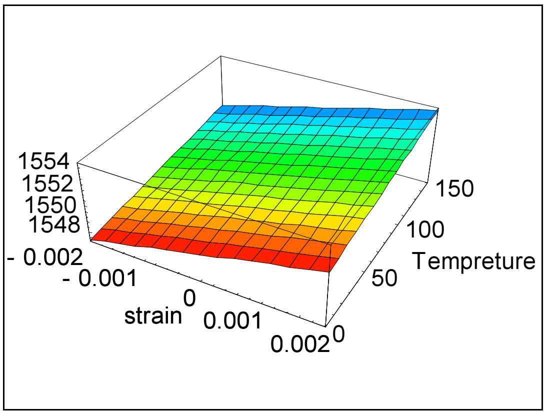

Fig. 9 Bragg wavelength at different values of temperature and strain.

From Fig. 9, it is shown at some points the effect of strain cancels the effect of temperature and a stable Bragg wavelength (= 1550 nm) is obtaind without any change. To simplify Fig. 9, one can use Fig. 10 (which illustrates the change in Bragg wavelength due to strain $\Delta\lambda_{BS}$) and Fig. 11 (which illustrates is plotted to illustrates the change in Bragg wavelength due to temperature). Then, using the two curves and Eq. (13), one can get the required strain at a certain temperature that achieves stable Bragg wavelength ($\Delta\lambda_B$ =0).

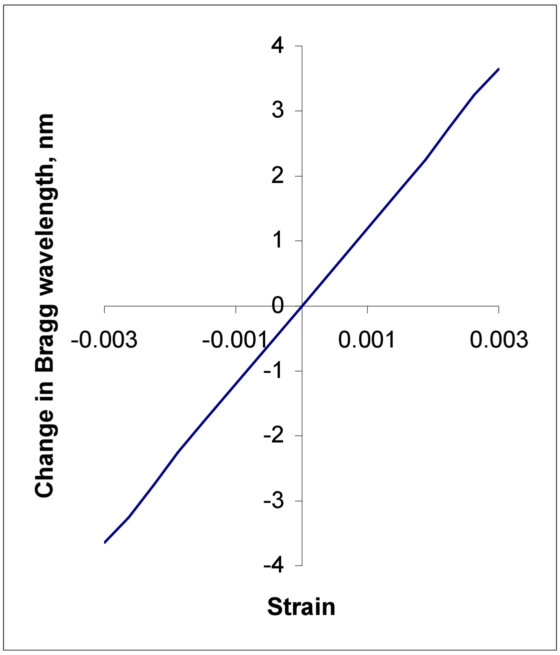

Fig. 10 The change in Bragg wavelength $\Delta\lambda_{BS}$ with strain.

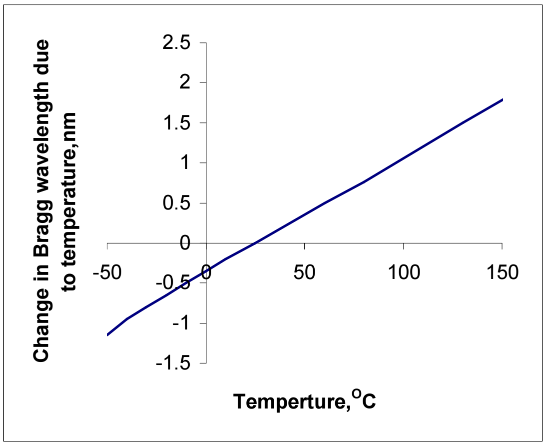

Fig. 11 The change in Bragg wavelength with temperature.

6. Compensating Bragg Wavelength Drift due to Both Pressure and Temperature (at Different Seawater Depths)

In Fig. 8, one can see the overall drift in Bragg wavelength due to both temperature and pressure at different seawater depths. It gives us the summation of $\Delta\lambda_{BS}$ and $\Delta\lambda_{BT}$ at different seawater depths. From Fig. 10, one can get the opposing strain values that give zero drift in Bragg wavelength.

7. Numerical results

From the previous figures some numerical results are concluded. For stable Bragg wavelength, Table 2 gives the required strain values when temperature effect is considered, while, Table 3 gives the required strain values when both temperature and pressure effects (combined in seawater depth) are considered.

Temperature,^{o}C	Strain,ξ
- 50	8.75×10^{-4}
- 30	6.2×10^{-4}
-10	3.75×10^{-4}
0	2.9×10^{-4}
25	0
60	$- 3.75\times10^{-4}$
80	$- 6.2\times10^{-4}$
110	- 0.001
130	- 0.00122

Table 2 Required strain at different temperatures.

Depth m	Temp ^{o}C	$\Delta\lambda_{BT}$ nm	$\Delta\lambda_{BP}$ nm	$\Delta\lambda_{BS}$ nm	Strain Mξ
1	29	0.05	0	-0.05	100
500	19	-0.07	-0.02	0.09	110
1500	4	-0.22	-0.047	0.267	2065
4000	-1.5	-0.38	-0.133	0.513	4130

Table 3 Required strain at different depths.

8. Conclusion

The FBG wavelength is affected by different environmental conditions such as temperature, pressure and strain. A stable Bragg wavelength is achieved by applying an artificial strain giving an opposite drift to that obtained due to temperature and pressure.

9. References

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