Journal of Computer and Communications, 2013, 1, 9-13
Published Online December 2013 (http://www.scirp.org/journal/jcc)
http://dx.doi.org/10.4236/jcc.2013.17003

The Circular Birefringence-Insensitive FBG Sensor for Weak Pressure

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Received August 2013

ABSTRACT

The influence of the circular birefringence on the measurement performance was analyzed based on the Polarization Properties of FBG in this paper. Due to the circular birefringence, the linear relationship between the max of *PDL* and pressure has been broken down. To estimate the cross sensitivity, a new parameter named relative peak of *PDL* (RP_{PDL}) is proposed. Under different circular birefringence, the same pressure sensitivity of sensor has been achieved. The theoretical analysis and experiment results prove that transverse strain sensor of FBG is insensitive to the circular birefringence by applying the RP_{PDL}. This research can be provided to useful and practical application.

Keywords: Circularly Birefringence; Polarization Propertied; FBG Weak Pressure Sensor; The Relative Peak of *PDL* (RP_{PDL})

1. Introduction

For both telecommunications and sensing purposes, FBG thus becomes important to characterize the polarization properties of FBG and their dependence on the wavelength [1-3]. Furthermore, this study can lead to the development of a new demodulation technique for FBG-based sensors. Caucheteur et al. have used polarization dependent loss (PDL) for transverse strain measurements [4,5]. The polarization dependent properties are also used for the magnetic field sensor [6].

Either way, there exist cross-sensitivity problems. In wavelength detection, the centre wavelength will change not only with the strain, but also with the temperature [7]. Similarly, in polarization detection, the polarization properties are influenced by the linear and circular birefringence [8,9]. Hence, we must take various kinds of measures to compensate or distinguish the cross-sensitivity problems. A number of techniques addressing this issue, such as dual-wavelength superimposed grating, two FBGs in different diameter fiber, hybrid FBG/long period grating, superstructure FBG and Fabry-Perot cavity method, have been reported [10-12]. Those methods provided some approaches to distinguish cross-sensitivity effect, but most of them needed specific gratings and special technique.

In this paper, the influence of the circular birefringence on the measurement performance was analyzed based on the polarization properties of FBG. To estimate the cross sensitivity, a new parameter named relative peak of PDL (RP_{PDL}) is proposed. The simulation and experiment results proved that the relative peak of PDL (RP_{PDL}) could effectively reduce the influence of circular birefringence.

2. Theoretical Models

2.1. Principle of Measurement

The polarization property of FBG has been widely used in the field of measurement. Here, we shortly introduce the principle of measurement.

The applied force causes a birefringence Δn, which is defined as the difference in refractive index between two orthogonal polarization modes called x and y modes (or eigenmodes). Due to the Δn, the x and y modes undergo different couplings through the grating. The total transmitted signal is the combination of the x and y mode signals. If there is only the linear birefringence, the Jones vector associated to the FBG transmitted signal is given by [5]:

$$\begin{pmatrix} E_{t,x} \\ E_{t,y} \end{pmatrix} = \begin{pmatrix} t_x & 0 \\ 0 & t_y \end{pmatrix} \begin{pmatrix} E_{i,x} \\ E_{i,y} \end{pmatrix} = \begin{pmatrix} t_x E_{i,x} \\ t_y E_{i,y} \end{pmatrix} \quad (1)$$

Where $(E_{i,x}, E_{i,y})^T$ is the Jones vector of the input signal and $t_{x(y)}$ denotes the transmission coefficient of $x(y)$ mode FBG [13].

Polarization Dependent Loss (*PDL*) is defined as the maximum change in the transmitted power by the grating as the input state of polarization is varied over all polarization states.

In this paper, the input signal is the linear state at π/4 between the $x(y)$ mode, $E_{i,x} = E_{i,y}$. In the case of Bragg gratings, it is easy to show that the *PDL* for the transmitted signal is given by [17]:

$$PDL(\lambda) = \left| 10\log_{10}\frac{T_x(\lambda)}{T_y(\lambda)} \right| = \left| 10\log_{10}\frac{E_{t,x}^2(\lambda)}{E_{t,y}^2(\lambda)} \right| \quad (2)$$

2.2. The Effect of Linear Birefringence

The study of Caucheteur et al. demonstrated that there is linear relationship between the peak of *PDL* and pressure [5]. But in practice, the fiber has intrinsic circular birefringence in the manufacturing process. Moreover, the induced circular birefringence can be caused by the shape, twisting and axial magnetic field of the fiber materials. The effect of circular birefringence must be taken into account when researching the performance of FBG weak pressure sensor based on the polarization properties.

Due to the circular birefringence, the Equation (1) will be modified as [18,19]:

$$\begin{pmatrix} E_{t,x} \\ E_{t,y} \end{pmatrix} = \begin{pmatrix} A & B \\ -B & A^* \end{pmatrix} \begin{pmatrix} t_x & 0 \\ 0 & t_y \end{pmatrix} \begin{pmatrix} E_{i,x} \\ E_{i,y} \end{pmatrix} = \begin{pmatrix} A & B \\ -B & A^* \end{pmatrix} \begin{pmatrix} t_x E_{i,x} \\ t_y E_{i,y} \end{pmatrix} \quad (3)$$

$$A = \cos(\frac{\Phi}{2}) + j\frac{\delta}{\Phi}\sin(\frac{\Phi}{2}) \quad (3\text{-}1)$$

$$B = \frac{2\Omega}{\Phi}\sin(\frac{\Phi}{2}) \quad (3\text{-}2)$$

$$\Phi = \left[\delta^2 + (2\Omega)^2 \right]^{1/2} \quad (3\text{-}3)$$

$$2\Omega = \left(\beta_R - \beta_L \right) l \quad (3\text{-}4)$$

$$\delta = \left(\beta_x - \beta_y \right) l \quad (3\text{-}5)$$

Where Φ, 2Ω and Δ are the phase shift of elliptically, circularly and linear polarized light, respectively. And we use the L and R subscripts to indentify the eigenmodes corresponding to the left and circularly polarized light.

According to the Equations (2) and (3), we will understand more clearly the effects of circular birefringence on the evolutions of *PDL*.

3. Simulation Results

We design a FBG with 1.455 of n_{eff}, 535 nm of Λ, 4mm of L and 1×10^{-4} of Δn. According to the given data, the simulation results can be got to analyze the influence of circular birefringence on the performance of proposed FBG sensor.

For purposes of analysis, some abbreviations were defined, such as B_{PDL}(the value of PDL that outside the FBG band), P_{PDL}(the peak value of PDL).

According to the Equations (1) and (2), **Figure 1** presents the PDL as a function of pressure. As expected, the increase of pressure leads to a general increase of PDL amplitudes. The P_{PDL} increase linearity with the pressure without circularly birefringence, which is shown in **Figure 2**.

Considering the influence of circular birefringence, the evolutions of *PDL* spectrums with pressure and circular birefringence are shown in the **Figure 3**. Due to the circular birefringence, the B_{PDL} is no longer zero and changed non-linearly with the circularly birefringence. Hence, the P_{PDL} does not increase linearly with the increasing of pressure, as shown in **Figure 3**. From **Figure 3**, it also can be seen that the P_{PDL} is influenced by the combination of circular and linear birefringence.

Up until now, it can be seen clearly that the linear relationship [5] between P_{PDL} and pressure was broken because of circular birefringence. In order to eliminate the effect, a new parameter named the relative peak of *PDL* (RP_{PDL}) is defined. The RP_{PDL} refers to the difference between the B_{PDL} and P_{PDL}. Without circular birefringence, the RP_{PDL} and P_{PDL} are the same.

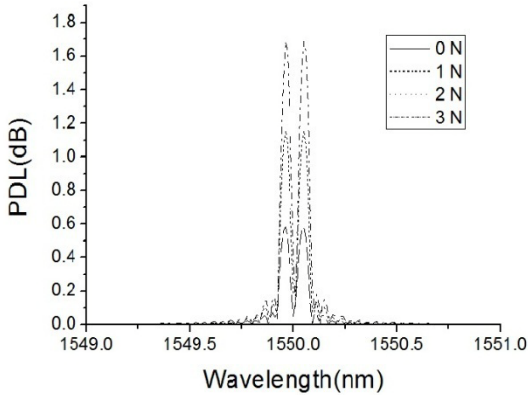


Figure 1. *PDL* versus wavelength at pressure without circularly birefringence.

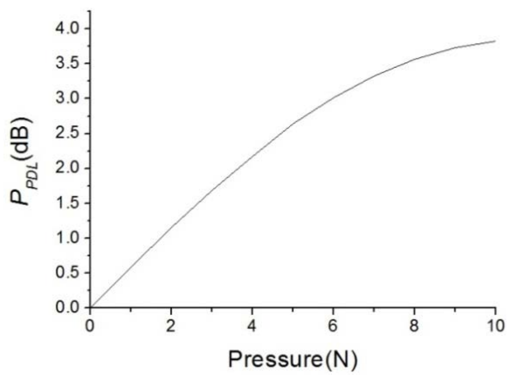


Figure 2. P_{PDL} versus pressure without circularly birefringence.

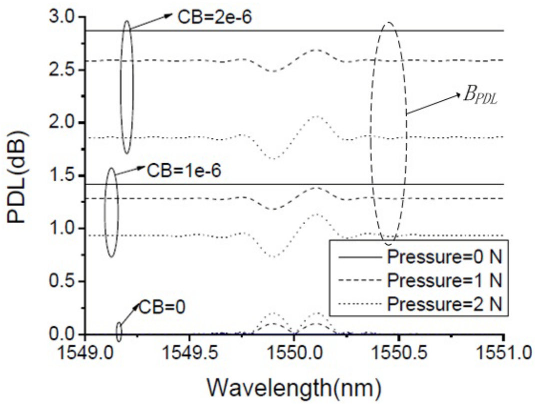


Figure 3. the evolutions of *PDL* at different circularly birefringence and pressure (CB = circular birefringence).

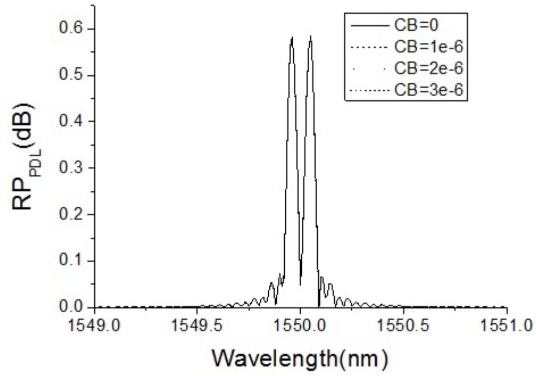


Figure 4. the evolutions of RP_{PDL} at different circularly birefringence with same pressure (CB = circular birefringence).

Under circular birefringence, the evolutions of RP_{PDL} were shown in **Figure 4**. From which it can be seen that the four RP_{PDL} lines were almost coincided under difference circular birefringence (solid, dash, dot and dash dot). **Figure 4** means that the RP_{PDL} is insensitive to the circular birefringence. Hence, the influence of circular birefringence on the performances of the FBG pressure sensors can be eliminated by using the RP_{PDL}.

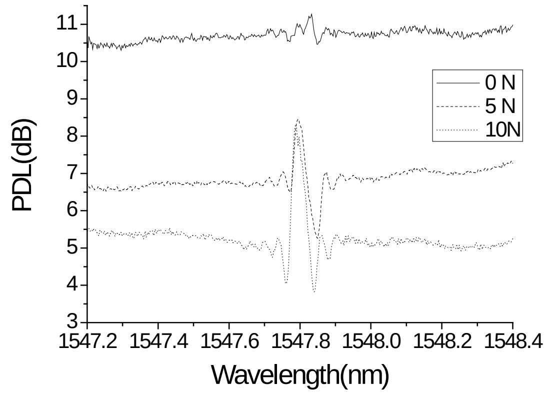
4. Experiment Results

The experimental data were then compared to theoretical evolutions. For that purpose, the experiment system was set up. The optical vector analyzer (OVA) is regarded as a light source, detector and processor. The FBG that used in experiment was designed and fabricated by our project group. The parameters of FBG are: n_{eff} = 1.455, Λ = 535 nm, $\Delta n = 5e^{-5}$ and L = 10 mm. The width of glass plate is the same size as the length of FBG. The fixture was used to generate the random circular birefringence by twisted the FBG, in this way, only the qualitative method can be used to analyze the circular birefringence. Due to the experimental condition limitations, the applied pressure was in the range 1 ~ 10 N by steps of 1 N. The results under two random conditions with different circular birefringence were calculated and analyzed in this section.

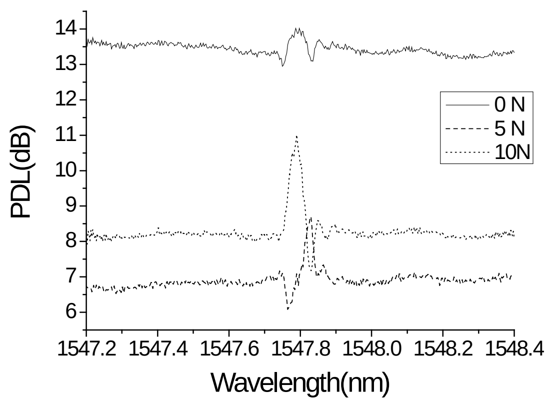
Using the optical vector analyzer whose precision is 10^{-5} (dB) in our experiment [20], the *PDL* evolutions for different pressure under two cases (different circular birefringence) are got and shown in **Figure 5**. The P_{PDL} becomes more and more obvious along with the increase of pressure. To observe **Figures 3** and **4**, the simulation results and experiment results were similar.

Based on different pressure and circular birefringence, the experimental data of the B_{PDL}, P_{PDL} and RP_{PDL} values respectively are given in **Table 1**.

From the **Figure 6**, we can find that the two set of data about RP_{PDL} and their fitting curves have a good agreement, which demonstrates that the RP_{PDL} is not influenced by the circular birefringence. In addition, due to the values of the fitting curves are increase monotonically with pressure, the RP_{PDL} can be used to retrieve the pressure. Based on calculations, the pressure sensitivity are same 0.229 dB/N. **Figure 6** also presents the theoretical results, the pressure sensitivity of which is 0.291 dB/N. The error between the experiment and theoretical results is caused by the manufacturing error of the FBG, such as the photo-induced birefringence [21,22]. The



(a) case 1



(b) case 2

Figure 5. *PDL* versus wavelength at pressure for two cases.

Table 1. the experimental results for two cases.

Pressure/N	Case 1			Case 2		
	B_{PDL}/dB	P_{PDL}/dB	RP_{PDL}/dB	B_{PDL}/dB	Peak/dB	RP_{PDL}/dB
0	10.94447	11.60567	0.6612	13.35158	14.01735	0.66577
1	9.7146	10.36974	0.65514	11.3351	12.0727	0.7376
2	6.94343	7.77878	0.83535	7.40321	8.23232	0.82911
3	6.7089	8.0723	1.3634	7.5258	8.8028	1.277
4	7.69596	9.12483	1.42887	8.1061	9.5944	1.4883
5	5.79927	7.7797	1.98043	6.86557	8.69737	1.8618
7	5.8658	7.91799	2.05219	6.98792	9.12278	2.13486
8	6.37788	8.56389	2.18601	7.97609	10.19856	2.2225
9	5.35373	7.74207	2.38834	6.08897	8.56583	2.47686
10	6.3616	9.35989	2.99829	7.97609	10.95309	2.977

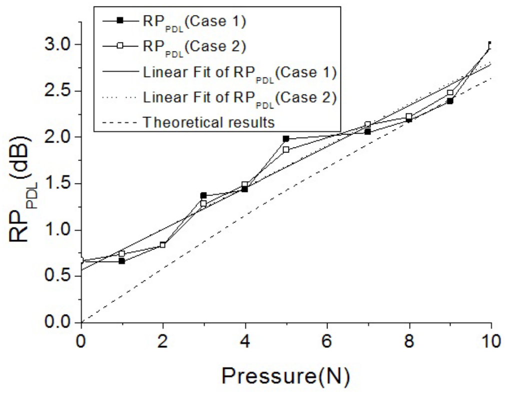


Figure 6. Evolution of RP_{PDL} in response to a change of pressure.

initial value of RP_{PDL} both are 0.66 under two conditions because of the intrinsic birefringence. The theoretical analysis and experiment results prove that the errors caused by the circular birefringence can be effectively eliminated by using the RP_{PDL}.

5. Conclusion

By analyzing the influences of the circular birefringence on the performance of the FBG pressure sensor, it is known that the nonlinear relationship between the P_{PDL} and the pressure can be caused by the circular birefringence, which affects the accuracy of the FBG pressure sensor based on the P_{PDL}. For overcoming this weakness, the parameter denoted by RP_{PDL} is proposed in this paper which can ensure the linear relationship between the RP_{PDL} and the pressure under the different circular birefringence, thus the pressure can be retrieved by the values of the RP_{PDL}. The theoretical analysis and experiment results prove that the errors caused by the circular birefringence can be effectively eliminated by using the RP_{PDL}. This research is helpful to the practical application of the FBG weak pressure sensor, such as underwater acoustic and liquid level measurement, etc.

6. Acknowledgements

This work was supported by the National Natural Science Foundation of china under GRANT 61271106, the Jiangsu Province Natural Science Foundation BK2012508 and China Postdoctoral Science Foundation funded project (2012M521850). We would like to thank Prof. Xiangfei Chen of Nanjing University for providing OVA in experiment.

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