Wavelength dependency of degree of polarization for PM-FBG and its application to temperature sensing

C. Caucheteur, M. Wuilpart, S. Bette, K. Chah, F. Lhommé, M. Blondel, P. Mégret

Faculté Polytechnique de Mons, Electromagnetism and Telecommunication Unit,
31 Boulevard Dolez, 7000 Mons, Belgium

We analyze the wavelength dependency of the degree of polarization for both the reflected and transmitted signals by a uniform Bragg grating written into a polarization maintaining fiber. Numerical simulations and experimental work are presented and a good agreement is shown between them. The potential realization of a demodulation technique using the degree of polarization in reflection as an encoding signal is finally reported.

Introduction

Fiber Bragg gratings are important components for both optical communications and sensing applications [1]. Many studies of their polarization effects have been reported in the past, including the compensation of the polarization mode disperion [2] and the measurement of polarization dependent loss [3]. We report here a theoretical and experimental study of the wavelength dependency of the degree of polarization (DOP) for both the reflected and transmitted signals by a uniform FBG written into a polarization maintaining fiber (PM-FBG). This study provides interesting results for the possible realization of a new demodulation technique for FBG sensors.

Theory and experiment

When a grating is written into a polarization maintaining fiber, the reflected and transmitted spectra are characterized by two main peaks corresponding to the eigenmodes also called the modes x and y :

$$\lambda_{Max,x} = 2(n_{eff,x} + \delta n)\Lambda \qquad \lambda_{Max,y} = 2(n_{eff,y} + \delta n)\Lambda \tag{1}$$

with

$$n_{eff,x} = n_{eff} + \frac{\Delta n}{2} \qquad n_{eff,y} = n_{eff} - \frac{\Delta n}{2} \tag{2}$$

where Λ is the grating period, n_{eff} is the effective refractive index of the fiber, δn is the index modulation and Δn is the fiber birefringence.
The DOP is an important quantity to describe partially polarized light. It is defined as the ratio between the intensity of the totally polarized component to the total intensity of the light. The DOP can be expressed in terms of Stokes parameters by :

$$DOP = \frac{\sqrt{S_1^2 + S_2^2 + S_3^2}}{S_0} \tag{3}$$

The parameters S_0, S_1, S_2 and S_3 are real numbers representing the state of polarization [4]. When experimentally measuring the DOP, the obtained value depends on the spectral width of the tunable laser source and on the measurement time needed by the apparatus. It is thus necessary to take into account these two parameters in the expression of the DOP. The Stokes parameters can be deduced from the electric fields components along the modes x and y [4]: S_0=$<|E_x|^2>$+$<|E_y|^2>$, S_1=$<|E_x|^2>$-$<|E_y|^2>$, S_2=2Re[$<E_xE_y^*>$] and S_3=2Im[$<E_xE_y^*>$]. In these expressions, $<E_{x(y)}>$ represents the mean value with time of the electric field along the mode $x(y)$. If we consider that the two eigenmodes are the 0 and $\pi/2$ rad linear polarization states and that the input state of polarization (SOP) is linear and defined by a Jones vector $(cos\theta, sin\theta)^T$, one can write :

$$\begin{pmatrix} E_{rx}(t) \\ E_{ry}(t) \end{pmatrix} = \begin{pmatrix} \int_{\omega_{min}}^{\omega_{max}} \rho_x(\omega) M_x e^{j(\omega t+\Theta_x)} d\omega \\ \int_{\omega_{min}}^{\omega_{max}} \rho_y(\omega) M_y e^{j(\omega t+\Theta_y)} d\omega \end{pmatrix} \tag{4}$$

$$\begin{pmatrix} E_{tx}(t) \\ E_{ty}(t) \end{pmatrix} = \begin{pmatrix} \int_{\omega_{min}}^{\omega_{max}} \tau_x(\omega) M_x e^{j(\omega t+\Theta_x)} d\omega \\ \int_{\omega_{min}}^{\omega_{max}} \tau_y(\omega) M_y e^{j(\omega t+\Theta_y)} d\omega \end{pmatrix} \tag{5}$$

The subscripts r and t represent the reflected and transmitted fields, respectively. θ is the angle between the input state of polarization and the mode x. $M_{x(y)}$ and $\Theta_{x(y)}$ are the amplitude and phase angle of the $x(y)$ component of the electric field. ω is the pulsation and t is the time. $|\omega_{max} - \omega_{min}|$ corresponds to the FWHM of the tunable laser source around its central wavelength. $\rho_{x(y)}$ and $\tau_{x(y)}$ denote respectively the reflection and transmission coefficients whose expressions are derived from the coupled mode theory [5].

Implementing the previous equations allows to study the wavelength dependency of the DOP. Since we want to make a comparison between theoretical and experimental evolutions, we have used parameters values computed from the reflected spectrum of the real FBG presented below by means of a simplex algorithm derived from [6]. The FBG used in this work was written into hydrogen-loaded bow-tie fiber through a 1060 nm period phase mask using a frequency-doubled Argon laser with 6 mm beam width. A polarization controller and an optical spectrum analyzer were used to measure the reflected peaks corresponding to the two eigenmodes. Their central wavelengths were equal to 1534.485 nm and 1534.884 nm, leading to a computed value of the birefringence of 3.78 10^{-4}.

The measurement set-up for the DOP is shown on Figure 1. A polarization controller (PC) was used to fix the input state of polarization of a fully polarized tunable laser source at $\pi/4$ rad between the eigenmodes of the PM-FBG. The FWHM of the laser source was measured equal to 8 pm. The tunable laser source was tuned from 1533 nm to 1536 nm with a wavelength step of 10 pm to ensure a good compromise of time and accuracy. A polarimeter measured the reflected and transmitted DOP. The output power of the source was fixed to its maximum available value ($\pm$ 0 dBm) to ensure that the reflected light had a sufficient intensity to be properly detected by the polarimeter. Figures 2 and 3 present the simulated and experimental evolutions of the DOP for the reflected and transmitted signals, respectively. The simulation was made with a wavelength step of 10 pm and considering that the FWHM of the source is 8 pm and that the integration time of the measurement device is 1 s. The input SOP was fixed at π/4 rad between the FBG eigenmodes.

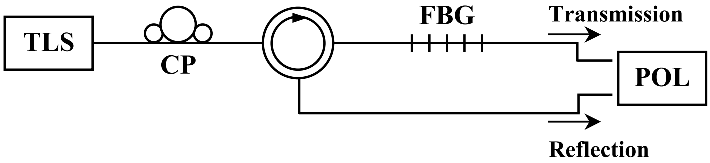

Figure 1: Measurement set-up for the DOP

The simulated and experimental curves have the same general behavior. The DOP for the reflected signal present drops every time the reflected spectrum is minimum. These drops come from the fast variations of the normalized Stokes parameters around the wavelengths at which the reflected spectrum is minimum. The DOP for the transmitted signal remains constant at a maximum value (99.55 %) in the transmission band of the grating. In the rejection band, it decreases a little.

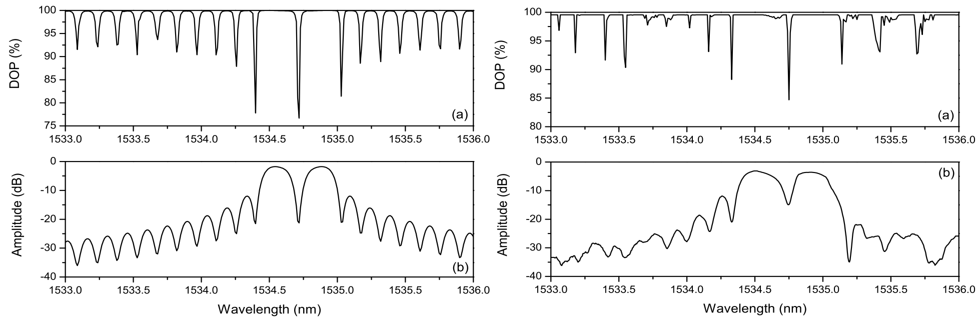

Figure 2: (a) DOP in reflection versus wavelength and (b) reflected spectrum. Left : Simulation with n_{eff} = 1.4521, Λ = 528.41 nm, L = 6 mm, $\delta n = 2\ 10^{-4}$ and $\Delta n = 3.7\ 10^{-4}$; Right : Experimental measurement

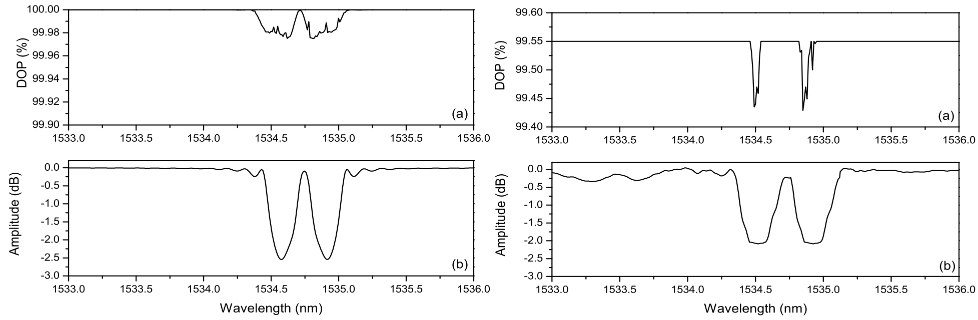

Figure 3: (a) DOP in transmission versus wavelength and (b) transmitted spectrum. Left : Simulation with n_{eff} = 1.4521, Λ = 528.41 nm, L = 6 mm, $\delta n = 2\ 10^{-4}$ and $\Delta n = 3.7\ 10^{-4}$; Right : Experimental measurement

Even if the behavior is qualitatively similar between the theoretical and experimental curves, some differences are observed. They can be explained by different reasons. First,

when experimentally fixing the input SOP, the PC is optimized to confer the same reflected peak heights to the two eigenmodes. This method is visual and the input SOP is therefore not exactly at $\pi/4$ rad between the eigenmodes as supposed in the simulations. Secondly, due to the high reflectivity of the grating, the reflected spectrum is not symmetrical. That can explain the asymmetry of the measured polarization properties. Finally, the accuracy on the measurement of high DOP values is guaranteed by the manufacturer of the polarimeter to be within $\pm$ 0.5 %. This certainly explains that the maximum measured value of the DOP always remains at 99.55 %.
The reflected DOP contains all the necessary information to be used as an encoding signal for an FBG sensor. In fact, when temperature or strain affects the grating, all the reflected wavelengths shift. Since the DOP minimums are correlated with the minimums of the reflected spectrum, the monitoring of one DOP minimum is sufficient to retrieve the information on the measurand. We monitored the evolution of the central DOP minimum (the DOP minimum corresponding to the minimum of the reflected spectrum situated between the two main peaks) in response to a change of temperature. We obtained a temperature sensitivity of 9.74 pm/$^\circ$C. Because the demodulation technique involves polarization effects, care was taken to avoid undesirable polarization variations. Except the sensor head, all the fibers were fixed. This precaution ensured a very good stability. The accuracy of this demodulation technique strongly depends on the accuracy of the laser source.

Conclusion

We presented the evolution with wavelength of the DOP in reflection and in transmission for a uniform PM-FBG. We compared theoretical and experimental evolutions and reported a good agreement between them. We also pointed out the possible realization of sensors based on the measurement of the reflected DOP.

Acknowledgment

Christophe Caucheteur is supported by the Fonds National de la Recherche Scientifique (FNRS). Patrice Mégret is supported by the Belgian Science Policy. The authors thank Damien Kinet from Multitel ASBL for the hydrogenation of the optical fibers.

References

[1] A. Othonos, K. Kalli, Fiber Bragg gratings : fundamentals and applications in telecommunications and sensing, Artech House (Norwood), 1999.

[2] S. Lee, R. Khosravani, J. Peng, V. Grubsky, D.S. Starodubov, A.E. Willner, J. Feinberg, "Adjustable compensation of polarization mode disperion using a high-birefringence nonlinearly chirped fiber Bragg grating", *IEEE Photonics Technology Letters*, vol. 11, pp. 1277-1279, 1999.

[3] Y. Zhu, E. Simova, P. Berini, C.P. Grover, "A comparison of wavelength dependent polarization dependent loss measurements in fiber gratings", *IEEE Transactions on Instrumentation and Measurement*, vol. 49, pp. 1231-1239, 2000.

[4] C. Brosseau, Fundamentals of polarized light, Wiley Inter-Science, 1998.

[5] T. Erdogan, "Fiber grating spectra", *Journal of Lightwave Technology*, vol. 15, pp. 1277-1294, 1997.

[6] C. Caucheteur, F. Lhommé, K. Chah, M. Blondel, P. Mégret, "Fiber Bragg grating sensor demodulation technique by synthesis of grating parameters from its reflection spectrum", *Optics Communications*, vol. 240, pp. 329-336, 2004.