Study of the polarization properties of fiber Bragg gratings for sensing purposes

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Bragg gratings written into standard single mode fibers can exhibit two types of birefringence: the birefringence induced by the UV photo-writing and the birefringence due to a transversal load. In both cases, it leads to differential group delay (DGD) and polarization dependent loss (PDL). We demonstrate that the PDL and DGD evolutions contain the information about the birefringence and could be used for sensing purposes.

Introduction

Fiber Bragg gratings (FBGs) allow the realization of important devices such as narrow optical filters and chromatic dispersion compensators. In the past few years, they have been proved to be excellent devices in high speed telecommunication systems as well as in optical sensing [1]. They are generally manufactured by irradiating one side of a photosensitive optical fiber to a UV interference pattern. It is admitted that this side-written fabrication process induces linear birefringence [2]. The transverse force contributes to increase the birefringence since the fiber cross section becomes elliptical. The birefringence Δn causes the orthogonal polarization modes to experience two different couplings within the grating [3]. Δn is spectrally manifested by two identical amplitude responses shifted in wavelength by a few picometers. Even if polarization control elements are used, this small wavelength shift is extremely difficult to perceive in the FBG spectrum. In practice, Δn leads to PDL and DGD [4].

Recently, we theoretically and experimentally studied the polarization properties of uniform FBGs written into both polarization maintaining fibers [5,6] and standard single mode fibers [7]. We reported that, in the case of FBGs written into standard single mode fibers, the PDL and DGD evolutions with wavelength contain more information about the birefringence value than the amplitude response.

When temperature and transverse force affect an FBG written into single mode fiber, they lead to comparable effects in the spectral evolution and their discrimination is consequently not possible. In this work, we demonstrate that the PDL and DGD wavelength evolutions could be used to overcome the above mentioned drawback.

Background theory

Birefringence in optical fibers is the difference in refractive index between a particular pair of orthogonal polarization modes (called x and y modes or eigenmodes). Their refractive index is defined by Eq. (1) where n_{eff} is the core effective refractive index.

$$n_{eff,x} = n_{eff} + \frac{\Delta n}{2} \quad ; \quad n_{eff,y} = n_{eff} - \frac{\Delta n}{2} \tag{1}$$

Due to Δn, the x and y modes undergo different couplings. The transmitted signal is thus the combination of the signals corresponding to the x and y modes. Considering a Cartesian coordinate system such that the reference axes correspond to the FBG eigenmodes, the Jones vector corresponding to the transmitted signal is defined by [5]:

$$\begin{pmatrix} E_{t,x} \\ E_{t,y} \end{pmatrix} = J.\begin{pmatrix} E_{i,x} \\ E_{i,y} \end{pmatrix} = \begin{pmatrix} t_x & 0 \\ 0 & t_y \end{pmatrix}\begin{pmatrix} E_{i,x} \\ E_{i,y} \end{pmatrix} = \begin{pmatrix} t_x E_{i,x} \\ t_y E_{i,y} \end{pmatrix} \tag{2}$$

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 the uniform FBG corresponding to the $x(y)$ mode. The expression of $t_{x(y)}$ can be derived from the coupled mode theory [8]:

$$t_{x(y)} = \frac{j\alpha_{x(y)}}{\hat{\sigma}_{x(y)} \sinh\left(\alpha_{x(y)}L\right) + j\alpha_{x(y)} \cosh\left(\alpha_{x(y)}L\right)} \tag{3}$$

$\alpha_{x(y)}$ and $\sigma_{x(y)}$ depend on $n_{eff,x(y)}$ and on the grating parameters (periodicity Λ, index modulation δn). L is the grating length. Power coefficients are given by $T_{x(y)} = |t_{x(y)}|^2$.
The PDL is defined as the maximum change in the transmitted spectrum when the input state of polarization (SOP) is varied over all polarization states. The DGD is defined as the difference in the group delay between the two eigenmodes. For FBGs, the PDL and DGD are given by:

$$PDL(\lambda) = \left|10\log_{10}(T_x(\lambda)/T_y(\lambda))\right| \qquad \Delta\tau(\lambda) = \left|\tau_x(\lambda) - \tau_y(\lambda)\right| \tag{4}$$

where the group delay $\tau_{x(y)}$ is the derivative, versus frequency ω, of the phase of $t_{x(y)}$.
Equations (4) are used to compute the PDL and DGD evolutions when Δn is modified.

Results and discussion

We show the results obtained for the following FBG parameters: L = 8 mm, Λ = 530 nm and $\delta n = 10^{-4}$. To simulate the transverse force effect, we let Δn vary from 10^{-6} to $5\ 10^{-4}$. Prior to discuss the results, let us mention that the obtained curves strongly depend on the FBG parameters. Fig. 1, 3 and 5 present the evolutions of the reflected spectrum, the transmitted PDL and the transmitted DGD when Δn is modified. For Δn values less than 10^{-4}, the birefringence is not perceived in the reflected spectrum: the reflected peaks overlap while the PDL and DGD evolutions already present two distinct peaks, located within the FBG reflection band. The evolutions of the peak amplitudes are depicted in Fig. 2, 4, 6 for the reflected spectrum, the PDL and the DGD, respectively. When Δn increases, for every evolution, the maximum amplitudes tend towards a constant value after a small ripple due to the presence of the secondary lobes in the FBG spectral evolution. Fig. 7 present the evolution of the wavelength spacing between the peaks. In the spectral evolution, the peaks cannot be distinguished until Δn reaches about $1.5\ 10^{-4}$ (the wavelength spacing remains null), rendering impossible simultaneous transverse force and temperature measurements. This is not the case in the PDL and DGD evolutions and thus, the monitoring of the maximum amplitudes as well as the wavelength spacing between the peaks in the PDL and DGD evolutions could be used to retrieve the transverse force value.

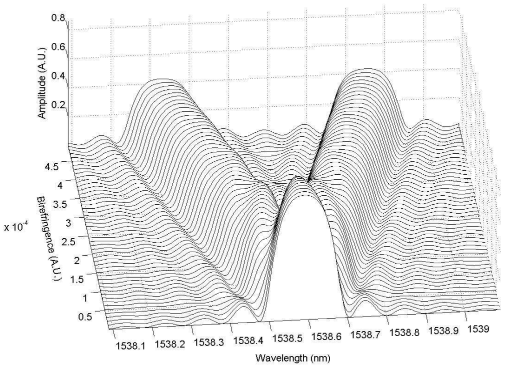

Figure 1. Spectral evolution in reflection versus Δn

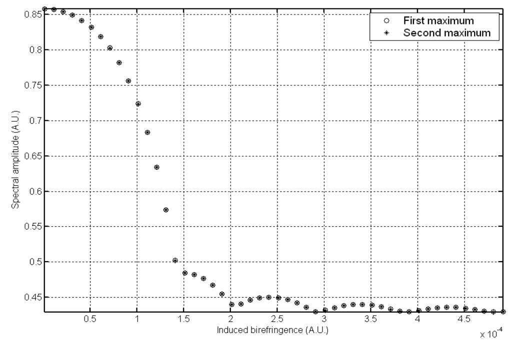

Figure 2. Maximum reflected amplitude versus Δn

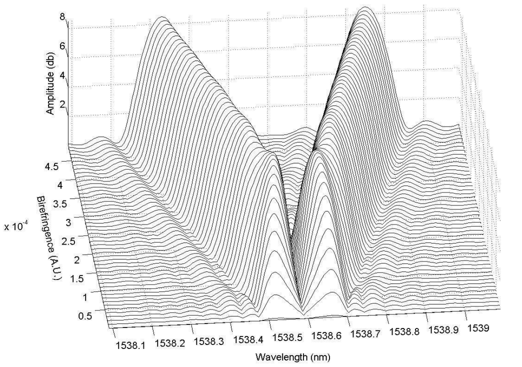

Figure 3. PDL evolution in transmission versus Δn

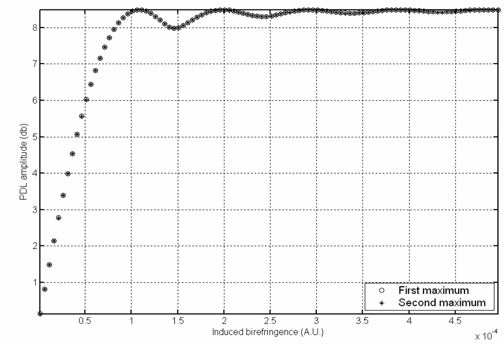

Figure 4. Maximum PDL amplitude versus Δn

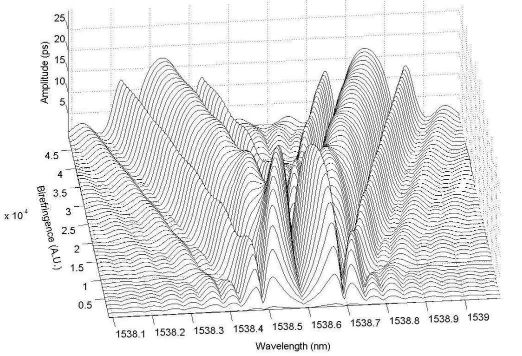

Figure 5. DGD evolution in transmission versus Δn

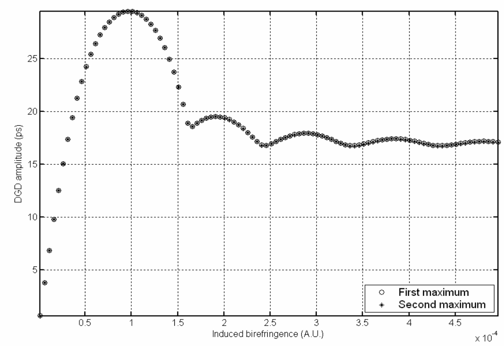

Figure 6. Maximum DGD amplitude versus Δn

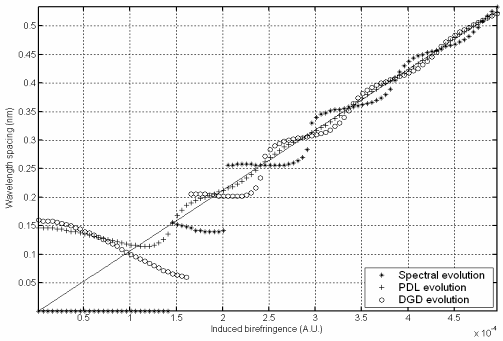

Figure 7. Wavelength spacing versus Δn

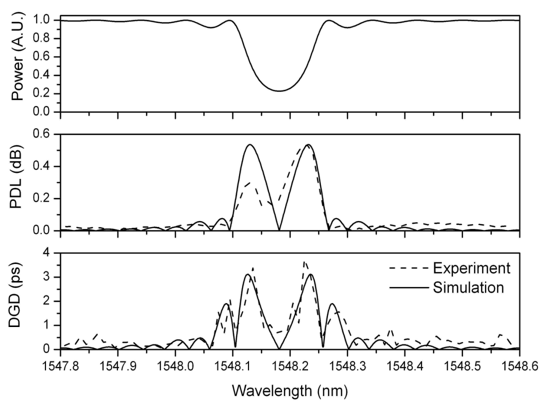

Figure 8. Experimental versus simulated evolution

For high Δn values, the wavelength spacing between the peaks reaches the same value for the spectral, PDL and DGD evolutions. This value is represented by a straight line in Fig. 7. It corresponds to the spacing between the x and y modes Bragg wavelengths and it is equal to $2\Delta n\Lambda$.

To experimentally confirm our theoretical study, we measured the PDL and DGD evolutions of unstrained uniform FBGs written into single mode fiber by means of a fully polarized tunable laser source and a polarimeter [7]. To confront simulated and experimental evolutions, we numerically reconstructed the physical parameters of the measured grating using the same technique as in [9].

Fig. 8 compares the experimental and numerically reconstructed evolutions for a uniform FBG whose physical parameters are: L = 1.04 cm, Λ = 532.955 nm, δn = 1.3 10^{-4} and Δn = 4 10^{-6}. A good agreement between experimental and simulated evolutions is obtained, proving the validity of our analysis.

Conclusion

By means of the coupled mode theory and the Jones formalism, we demonstrated that the PDL and DGD evolutions contain useful information about the birefringence value. Finally we compared the theoretical results with the experimental obtained values to confirm the validity of our study.

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