Demodulation technique for transverse strain FBG sensor based on the measurement of the polarization properties

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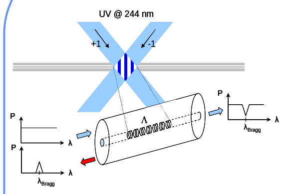
Birefringence in fiber Bragg gratings leads to polarization dependent loss and differential group delay. We demonstrate that the polarization properties of uniform Bragg gratings written into standard single mode fibers can be advantageously used to obtain temperature-insensitive transverse force measurements, which is not possible through conventional spectral measurements.

Theoretical background

Operating principle of FBGs – Birefringence effect



Fibre Bragg Grating (FBG) : Local **modulation of the core refractive index of an optical fibre** created by interference of UV light.

In reflection, an FBG acts as a mirror selective in wavelength around the **Bragg wavelength**

Because of the birefringence, the transmitted spectrum is composed of **two overlapping resonant peaks** whose central wavelengths are:

$$\lambda_{Max,x(y)} = 2(n_{eff,x(y)} + \delta n)\Lambda \quad \text{with} \quad n_{eff,x} = n_{eff} + \frac{\Delta n}{2} \quad \text{and} \quad n_{eff,y} = n_{eff} - \frac{\Delta n}{2}$$

- Λ is the grating period
- n_{eff} is the mean effective refractive index of the fiber - δn is the core index modulation
- Δn is the fiber birefringence

The wavelength spacing between the two peaks is given by $\Delta\lambda_{Bragg} = 2\Delta n\Lambda$

In the case of induced-birefringence, $\Delta n \sim 5\ 10^{-6}$ and $\Lambda \sim 500$ nm → $\Delta\lambda_{Bragg}$ **~5 pm**

Δn has two remarkable effects: it induces **PDL** and **DGD**

Theoretical analysis: Coupled mode theory and Jones vector formalism

Considering a Cartesian coordinate system such that the reference axes correspond to the FBG eigenmodes, the Jones vector corresponding to the transmitted signal is given by

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

$(E_{i,x}\ E_{i,y})^T$ is the Jones vector of the input signal

$t_{x(y)}$ is the transmission coefficient of the FBG corresponding to the x(y) mode

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

$\alpha_{x(y)}$ and $\sigma_{x(y)}$ depend on $n_{eff,x(y)}$, Λ, and index modulation δn. $T_{x(y)} = |t_{x(y)}|^2$

PDL: Maximum change in the transmitted spectrum when the input state of polarization is varied over all polarization states

DGD: Difference in the group delay between the two eigenmodes

$$PDL(\lambda) = \left|10\log_{10}(T_x(\lambda)/T_y(\lambda))\right|$$

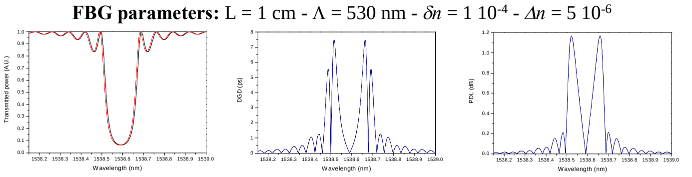
$$\Delta\tau(\lambda) = \left|\tau_x(\lambda) - \tau_y(\lambda)\right|$$

$\tau_{x(y)}$ is the derivative, versus ω, of the phase of $t_{x(y)}$

Use of the PDL and DGD evolutions for sensing purposes

Typical PDL and DGD evolutions with wavelength

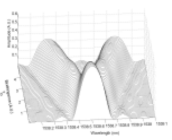
FBG parameters: L = 1 cm - Λ = 530 nm - $\delta n = 1\ 10^{-4}$ - $\Delta n = 5\ 10^{-6}$



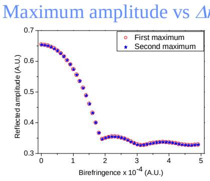
Influence of the birefringence value on the spectral evolutions

FBG parameters: L = 5 mm - Λ = 530 nm - $\delta n = 1\ 10^{-4}$ - $\Delta n = [5\ 10^{-6}\ 5\ 10^{-4}]$

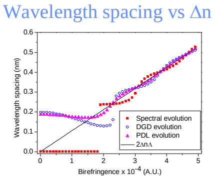
Reflected spectrum vs Δn



Maximum amplitude vs Δn

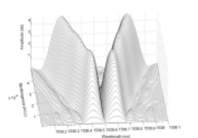


Wavelength spacing vs Δn

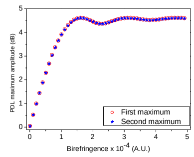


- For high Δn values, the wavelength spacing between the peaks reaches the same value for the spectral, PDL and DGD evolutions. It corresponds to the spacing between the two Bragg wavelengths ($2\Delta n\Lambda$)
- The evolutions strongly depend on the FBG parameters!

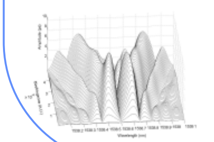
Transmitted PDL vs Δn



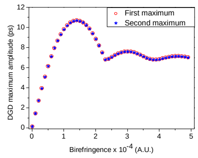
Maximum PDL vs Δn



Transmitted DGD vs Δn

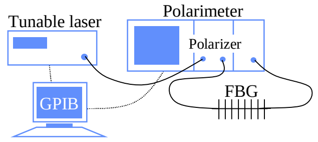


Maximum DGD vs Δn



- For $\boldsymbol{\Delta n < 10^{-4}}$, the reflected peaks overlap while the **PDL and DGD evolutions present two distinct peaks**, located within the FBG reflection band
- When Δn increases, for every parameter, the **maximum values tend to a constant** after a ripple due to the secondary lobes of the FBG spectrum
- In the spectral evolution, contrary to PDL and DGD evolutions, the peaks overlap until Δn =~ 1.5 10^{-4}

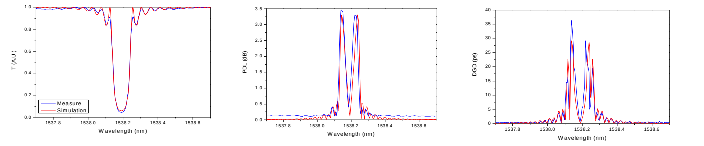
Experimental set-up



- Tunable laser source and polarimeter followed by a polarizer controlled by a computer
- Jones matrix eigenanalysis
- Wavelength step : 10 pm
- Fibers fixed to avoid polarization fluctuations

Experiment versus simulation

To confront simulated and experimental evolutions, we reconstructed the grating parameters using a numerical reconstruction tool based on the Nelder-Mead simplex algorithm

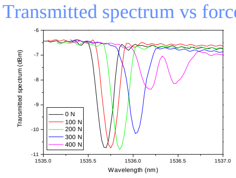


Reconstructed parameters: L = 15 mm - Λ = 529.775 nm - $\delta n = 1.4\ 10^{-4}$ - $\Delta n = 8\ 10^{-6}$

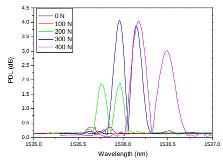
Transverse force influence on the PDL and DGD evolutions

- 5 mm long FBG written into hydrogen-loaded SMF-28
- FBG placed between two metal plates

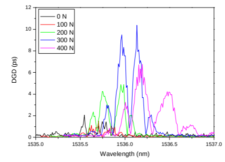
Transmitted spectrum vs force



PDL vs force

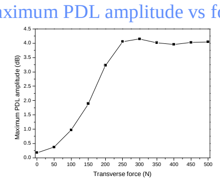


DGD vs force

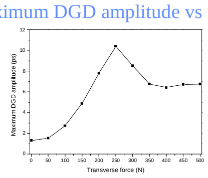


- Transverse force values under 300 N lead to a shift of the central lobe in transmission
- They lead to a monotonic increase of the PDL and DGD main lobe amplitudes
- **The obtained behavior is in good agreement with the simulation** (see left column)

Maximum PDL amplitude vs force

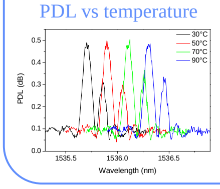


Maximum DGD amplitude vs force

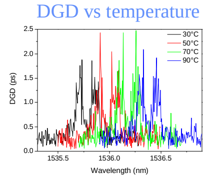


Temperature influence on the PDL and DGD evolutions

PDL vs temperature



DGD vs temperature



- FBG placed at varying temperatures between 30°C and 100°C
- The maximum amplitudes of the PDL and DGD evolutions with wavelength remain nearly constant when the temperature evolves

Conclusions

- PDL and DGD evolutions contain useful information about the birefringence value and can be used for temperature-insensitive transverse force sensing purposes
- A good agreement between experiment and simulation was reported

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