Optimization of fiber Bragg grating physical parameters for polarization-assisted transverse strain measurements

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In fiber Bragg grating (FBG) sensors, the evolution of the wavelength maximum polarization dependent loss (PDL) amplitude is used to determine the birefringence of the fiber. For low birefringence value, the relation between the wavelength maximum PDL amplitude and the birefringence is nearly linear and so it can be approximated by a straight line with a slope that depends on the physical parameters of the FBG. An analytical formula for this slope is derived. The comparison of the analytical approximation with simulations values for weak gratings gives errors below 0.05 dB for a birefringence up to $1.5\,10^{-5}$.

Introduction

Fiber Bragg grating sensors have become very common and recently new sensors that take advantage of the polarization properties of the fiber Bragg grating response have been developed [1, 2]. The polarization-assisted sensors use the value of the maximum polarization dependent loss (PDL) to determine the birefringence created in the fiber by the physical parameter (load,magnetic field) to be determined. The relationship between the maximum value of the PDL and the birefringence is nearly linear for small values of the birefringence. The sensor will be used in this range. The value of the slope of the maximum PDL versus birefringence depends on the parameters of the FBG and it determines the accuracy and the operating range of the sensor. The value of the slope is therefore crucial in the design of polarization-assisted sensors. In this work, we determine an approximate analytical formula for this slope that helps designing such sensors.

Birefringence and polarization dependent loss (PDL)

The response of a uniform FBG in transmission was analyzed in details in [3]. The grating parameters δn, L, Λ and the coefficients α, κ, $\hat{\sigma}$ used in the following come from [3]. When the fiber is not perfectly symmetric due to intrinsic dissymmetry or external factors such as strain, it exhibits birefringence and the response of the FBG then depends on the state of polarization of light that is launched into the fiber Bragg grating (FBG). The response of the FBG can be determined by separating all polarizations at the entrance in the basis of the two FBG eigenstates (labelled x and y). The eigenstates x and y have respectively an effective refractive index of the core given by n_{eff} and $n_{\text{eff}} + \Delta n$ with Δn the birefringence of the fiber. The PDL is given by [4]:

$$PDL = \left| 10 \log_{10} \frac{T_x}{T_y} \right| \tag{1}$$

where T_x and T_y are the transmission intensities spectrum for the 2 eigenstates.

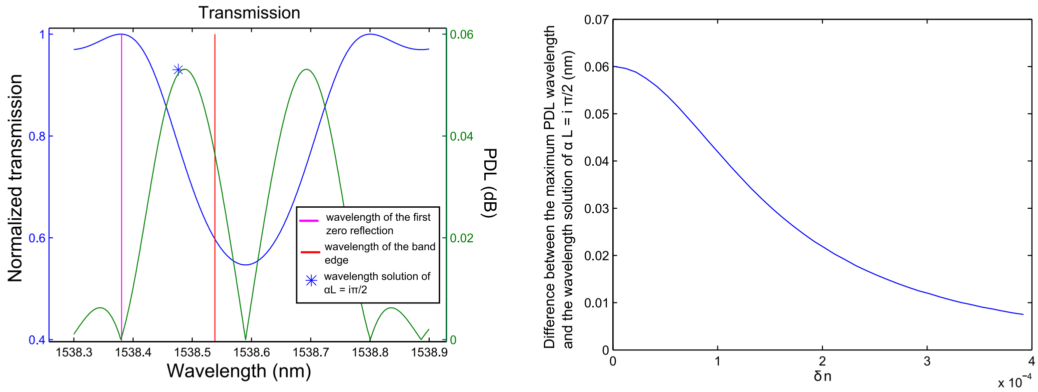
Determination of an approximate analytical formula for the slope between the PDL maximum and the birefringence

To find an approximate formula for the slope, we proceed in 3 steps. First, we define an approximate wavelength position for the maximum of the PDL when the birefringence is small. Then, we compute the slope for each wavelength by calculating $\frac{d\,(PDL)}{d\,(\Delta n)}$ evaluated for $\Delta n = 0$. Finally, we combine the two former points and simplify the formula obtained. In general, to find a maximum we equal the derivative to 0 but in the case of the PDL the equation to be solved contains hyperbolic functions and the analytical solution cannot be found easily. Instead of finding an exact solution, we approximate the wavelength of the maximum to be such that $\alpha L = i\pi/2$. This hypothesis is justified by the following considerations:

1. The PDL maximum is between 2 well defined points. The first one is the band edge characterized by $\alpha L = 0$ and the second one is the first zero of the reflection that corresponds to $\alpha L = i\pi$. The point such that $\alpha L = i\pi/2$ is then a good estimation of the wavelength of PDL maximum. The band edge and the first zero of reflection of an FBG are shown in Figure 1a.

2. We see on Figure 1a that the value of the PDL varies smoothly near its maximum value so a small error in the position of the PDL maximum does not strongly affect the slope. This is not the case for strong gratings (reflectivity $\geq 98\%$) in which a small error in the wavelength position of the PDL maximum will result in a strong error in the slope.

3. For usefulness, the expression of the slope is reduced by taking $\alpha L = i\pi/2$ so as to suppress the hyperbolic function.



(a) (b)

Figure 1: (a) Transmission spectrum versus wavelength and PDL versus wavelength with the band edge and the fist zero also plotted (b) Wavelength difference between the max PDL wavelength and the $\alpha L = i\pi/2$ wavelength

For FBGS, the mean modulation index is small compared to the effective refractive index of the core $\delta n << n_{\text{eff}}$ and also the period of the grating is small compare to the FBG length $\Lambda << L$. When determining the wavelength (λ_{app}) such that $\alpha L = i\pi/2$, we only keep the first order terms in δn and Λ. We obtain for λ_{app}:

$$\lambda_{app} = \frac{4L\Lambda n_{\text{eff}}(2\delta n + n_{\text{eff}})}{2L(n_{\text{eff}} + \delta n) + (L^2\delta n^2\nu^2 + 4\Lambda^2 n_{\text{eff}}{}^2)^{1/2}} \tag{2}$$

Inserting equation (2) in $\left.\frac{d\,(PDL)}{d\,(\Delta n)}\right|_{\Delta n=0}$ yields the slope S :

$$S = \frac{-10}{\ln(10)} \frac{4\pi(\hat{\sigma}^2 + \alpha^2)}{\alpha^2 \lambda_{\text{app}} \hat{\sigma}} = \frac{10}{\ln(10)} \frac{16L^2\kappa^2}{\pi \lambda_{\text{app}} \hat{\sigma}} \tag{3}$$

with $\alpha^2 = -\pi^2/4L^2$.
Equation (3) can be further simplified by developing κ and replacing λ by $2\Lambda n_{eff}$ everywhere except in $\hat{\sigma}$ (because $\hat{\sigma} = 0$ if we replace λ by $2\Lambda n_{eff}$) :

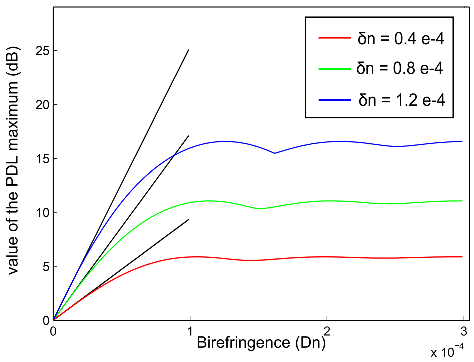
$$S = \frac{10}{\ln(10)} \frac{16L^2\pi\nu^2\delta n^2}{(2\Lambda n_{\text{eff}})^3 \hat{\sigma}} \tag{4}$$

Developing and comparing the remaining terms allow additional simplifications :

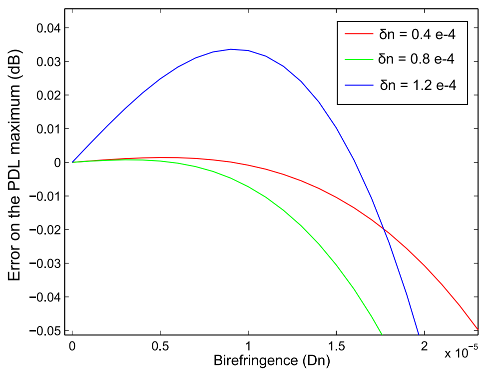
$$S = \frac{40}{\ln(10)} \frac{L^3\delta n^2\nu^2}{\Lambda^2 n_{\text{eff}}{}^2 (L^2\delta n^2\nu^2 + \Lambda^2 n_{\text{eff}}{}^2)^{1/2}} \tag{5}$$

Results

In this section, we compare the maximum value of the PDL with the value given by the linear approximation. The absolute errors between the linear approximation and the real value are shown in Figure 2b and stay below 0.05 dB for a birefringence up to $1.5\,10^{-5}$.



(a)



(b)

Figure 2: (a) Evolution of the maximum PDL with birefringence for 3 different values of δ_n (b) Absolute error for different values of δn

Conclusion

We presented an analytical formula that links the parameters of an FBG with the value of the slope between the birefringence and the maximum value of the PDL. The difference between the linear approximation and simulation value gives errors below 0.05 dB for a birefringence up to $1.5\,10^{-5}$. The formula is simple enough to be helpful for designing polarization-assisted FBG sensors.

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