Performance comparison between two polarization-assisted techniques to measure non-uniform load profiles with chirped FBGs

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In some applications it is important to measure the stress profile on a few centimeters. Two different methods using the polarization properties (differential group delay (DGD) in reflection and polarization dependent loss (PDL) in transmission) of CFBGs have been recently proposed to perform such measurements. Despite their apparent similarity, each method has different advantages. A comparison between these two methods shows that the PDL method is more precise for deep variations and is less sensitive to the apodization quality. The DGD method has the advantage to be performed in reflection as well as being more suitable for slowly increasing force.

Introduction

Fiber Bragg gratings (FBGs) are nowadays used to measure loads [1]. Despite being mainly used to measure pointwise load, FBGs are also suited to determine load profiles on the centimeter scale. To perform such measurement, chirped FBGs (CFBGs) are used since there is a one-to-one correspondence between the load position and the wavelength [2]. We have recently proposed two methods using the polarization properties of CFBGs to perform such measurement [3-4]. These two methods have the advantage not to require any demodulation process to retrieve the load profile. The first method uses the measurement of the differential group delay (DGD) in reflection. This parameter is directly proportional to the load. The profile is therefore directly visible on the DGD spectrum. The second one is based on the polarization dependent loss (PDL) in transmission. In this case, it is the integration of the PDL spectrum over the wavelength that gives the load profile. Despite their apparent similarity, each of the two methods has different advantages and drawbacks.

The aim of this article is to describe these advantages and drawbacks. After a brief description of the PDL and DGD methods, these two methods are compared using simulations. In the simulations, different load profiles are applied on the same CFBG and the two methods are thereafter used to retrieve the load. Finally an experimental comparison between the two methods is reported.

Description of the two methods based on polarization properties measurement

The effect of the load *F(z)* on the fiber is the creation of birefringence. The value of this birefringence $\Delta n(z)$ is directly proportional to the load [5]:

$$\Delta n(z) = \left| \frac{2n_{\text{eff}} F(z)}{E\pi b} (1+v)(p_{11} - p_{12}) \right| \quad (1)$$

Where n_{eff} is the effective refractive index, *E* the Young modulus, *b* the optical fiber radius, p_{11} and p_{12} the photoelastic coefficients, *v* the Poisson's coefficient.

The birefringence conducts to a different spectral response of the FBG depending on the polarisation. Two eigenmodes of polarization appear and their spectral responses are denoted by T_x (R_x) and T_y (R_y), respectively. The objective of the two methods is the determination of the birefringence at each point of the grating $\Delta n(z)$ created by the load. The load is thereafter computed using Eq. (1).
The two methods use the link that inherently exists in CFBG between the position z and the wavelength λ. This link that allows to convert the wavelength information in spatial information comes from the linear evolution of the Bragg wavelength $\lambda_{Bragg} = 2n_{\text{eff}}\Lambda$ with the position:

$$\lambda_{\max} = 2\left(n_{\text{eff}} + \delta n\right)\left(\Lambda_0 + Cz\right) = \lambda_{Bragg}\frac{\left(n_{\text{eff}} + \delta n\right)}{n_{\text{eff}}} \tag{2}$$

With C the chirp, $\lambda_{\max}$ the wavelength of the maximum reflectivity, δn the amplitude of the refractive index variation and Λ_0 the initial period of the grating.
The first method uses the PDL in transmission that is the logarithm of the ratio between the transmission amplitude spectra of the 2 eigenmodes. A direct relationship exists between the integration over the wavelength of the PDL spectrum in which the sign is keep (noted ***PDL***) and the load value. This linear relation is given by:

$$\int_0^{\eta} \boldsymbol{PDL}(\lambda)d\lambda = -\frac{20}{\log(10)}\frac{\kappa_0^{\,2}\Lambda_0^{\,3}}{Cn_{\text{eff}}}\left(n_{\text{eff}} + \delta n\right)\Delta n(z) \tag{3}$$

With $\eta = \lambda_{\max}(z)$, and $\kappa_0 = \dfrac{\delta n\,\pi}{2n_{\text{eff}}\Lambda_0}$.

The second method uses the DGD in reflection that is defined as the absolute value of the difference between the group delays of the two eigenmodes. The DGD in reflection is directly proportional to the birefringence value [5]:

$$\Delta n(z) = \frac{DGD\left(\lambda_{\max}(z)\right)}{2\left(\Lambda_0 + Cz\right)p_\tau} \tag{4}$$

With p_τ the slope of the group delay when no load is applied.

Comparison of the two methods using transfer matrix simulation

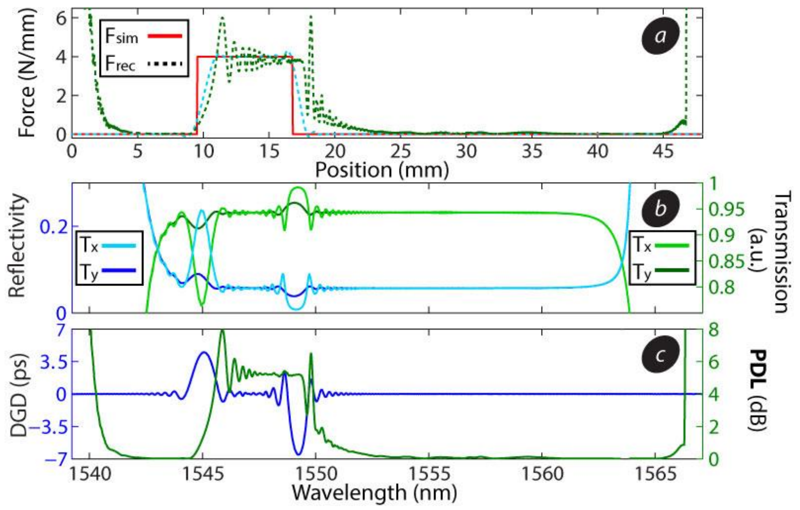

Fig. 1: a) Rectangular load profiles applied on the CFBG and reconstructed load obtained by the DGD (dark green) and PDL method (light blue); b) Transmission and reflection spectra of the two eigenmodes under the load profile displayed in a; c) PDL and DGD response under the force profiles displayed in a).

To compare the two methods, we have simulated a rectangular load profile (Fig. 1a) and a Gaussian load profile (Fig. 2a) using the transfer matrix method [6]. We denote F_{sim} the profile injected in the simulation. Figures 1b and 2b show the spectral responses T_x and T_y while Fig. 1c and 2c show the DGD in reflection (blue) and the PDL in transmission (green) for the rectangular and the Gaussian profile, respectively. The two methods are thereafter used to reconstruct the load profiles. The reconstructed load profile (F_{rec}) is displayed in red for the PDL method and in green for the DGD. We can see on the figures that the PDL method better reproduces the profile but is less suited for load profile that varies slowly since the PDL created is small in this case.

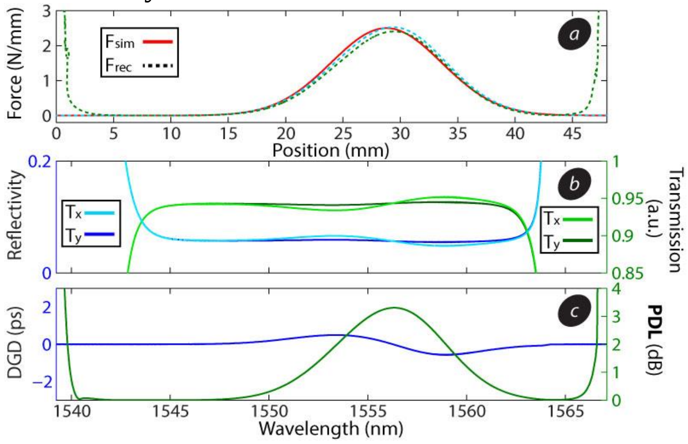

Fig. 2: a) Gaussian load profile applied on the CFBG and reconstructed load obtained by the DGD (dark green) and PDL method (light blue); b) Transmission and reflection spectrum of the two eigenmodes under the load profiles displayed in a); c) PDL and DGD response under the force profiles displayed in a).

The influence of the modulation amplitude and the chirp on the reconstruction with the DGD method has already been analysed in [3]. For the PDL method, the amplitude modulation must be such that the transmission is around 0.5 to obtain high modification of the transmission induced by the load. If it is not the case such as in Fig. 1, the amplitude of the modification in the part that approaches 0 or 1 will be reduced. As seen in Fig. 3, a reduction of the chirp value conduct to an increase of the sensitivity. It is accompanied by a decrease of the spatial resolution (although not well perceived on the figure).

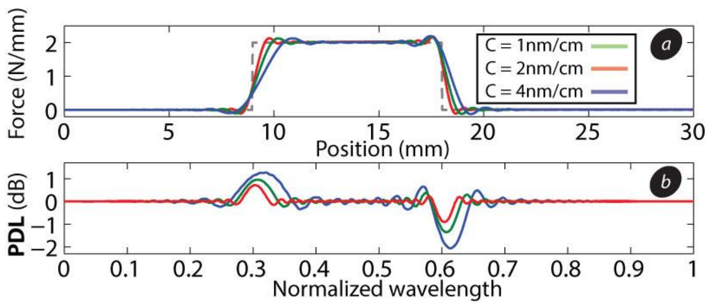

Fig. 3: a) Reconstructed force profile for 3 different chirp values; b) PDL spectra for the 3 chirp values.

Experimental results comparison

In the experiment a rectangular load profile of 6mm has been applied on a CFBG using a U-shape metal plate. Five different load values (11.2N, 16.2N, 21.2N, 26.2 and 31.2N) have been applied. The CFBG responses were analysed by means of an optical vector analyser that provides the Jones matrix in transmission of the CFBG. The chirp of the CFBG was considered as known with a value of C = -1.96nm/cm. The other CFBG parameters (the DC index change, the grating length and the initial period of the grating) were reconstructed from the unloaded CFBG amplitude spectrum. Figure 3 displays the reconstructed load profile for the two methods. As we can see on this figure, both methods well reproduce the applied profile as well as the increase of the reconstructed load value when the applied load is increased. However in the 26.2N and 21.2N case, an erroneous decrease appears near 10 mm with the DGD method. We believe that it arises from the noise. The PDL method seems less affected by the noise.

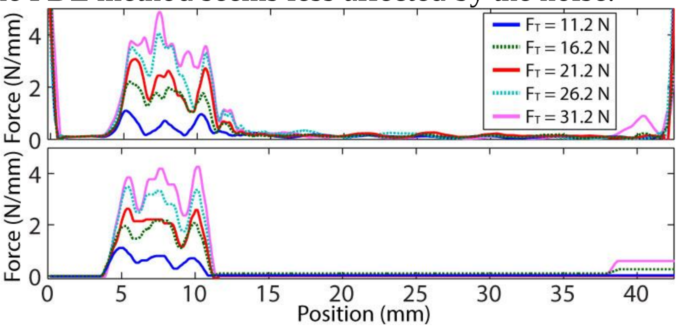

Fig 4: a) Reconstructed load profile from the DGD spectrum; b) Reconstructed load profile from the PDL spectrum.

Conclusion

In this paper, we have compared two methods (based on DGD and PDL) to measure a load profile that uses the polarization properties of the spectral response of a CFBG. The two methods are fundamentally different since the DGD method is based on a phase measurement in reflection while the PDL method uses an amplitude measurement in transmission. Beside these differences, the simulations performed have shown that the PDL method has a higher spatial resolution but is less sensitive than the DGD method to determine load profile with small variations. As in the DGD method, a smaller value of chirp for the CFBG increases the sensitivity but decreases the spatial resolution of the PDL method. Finally, an experimental comparison has been performed. The experiment shows that both methods reproduce correctly the applied rectangular profile of load, with their respective advantages.

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