Experimental demonstrations of the relationship between chromatic dispersion and differential group delay in weakly birefringent fibre gratings

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For weakly birefringent fibre gratings, the presence of birefringence can be hardly detected in the amplitude response. However, it leads to polarisation dependent properties such as differential group delay (DGD). In this case, we report that the wavelength dependency of DGD corresponds to wavelength dependency of CD weighted by the birefringence value. We show that this relationship between DGD and CD can be advantageously exploited to get the grating birefringence. Experimental results are finally reported in good agreement with the theory.

Complete characterization of fibre Bragg grating (FBG) and long period grating (LPG) includes the measurement of both its amplitude and phase response. Phase analysis is generally conducted through group delay or chromatic dispersion (CD) measurement. In presence of birefringence, it is also essential to characterize polarization dependent parameters such as polarization dependent loss (PDL) and differential group delay (DGD) of gratings. While the gratings PDL has been analyzed a few years ago [1], there is currently a great interest for the DGD: results have recently been presented for UV written FBGs [2], FBGs and LPGs written using a femtosecond pulses laser in single mode [3,4] and photonic crystal [5] fibres. In most case, DGD has been experimentally analyzed without the possibility to compare it with theory.

In this paper, we show that it is possible to obtain a deeper knowledge of the grating DGD based on the measurement of the CD evolution. For that purpose, we first demonstrate the relationship that exists between CD and DGD for fibre gratings exhibiting weak birefringence. This relationship between CD, DGD and birefringence is then advantageously exploited to get the grating birefringence. Experimental results are finally reported.

Birefringence Δn in optical fibres is defined as the difference in refractive index between a particular pair of orthogonal polarization modes (called eigenmodes or modes x and y) so that $n_{eff,x} - n_{eff,y} = \Delta n$. For the case of fibre gratings, there exist different sources of birefringence: intrinsic fibre birefringence, photo-induced birefringence due to the manufacturing process [6], and birefringence induced by applying transversal load [7]. In the following, Δn parameter represents the global birefringence resulting to these different contributions.

Let us consider a fibre grating characterized by its complex transmission function $t = |t|.e^{j\theta}$ and its group delay response τ defined as the derivative, versus the pulsation, of the grating phase $\tau = d\theta/d\omega$. The presence of birefringence causes the two grating eigenmodes to experience different couplings through the grating and leads to two different complex transmission functions t_x and t_y. These two functions are characterized by a nearly identical transmission spectrum shifted in wavelength by a quantity $\Delta\lambda$ such that $t_y(\lambda) \approx t_x(\lambda+\Delta\lambda)$ [2]. In particular, the group delays τ_x and τ_y associated to each eigenmode respect the same relationship: $\tau_y(\lambda) \approx \tau_x(\lambda+\Delta\lambda)$.

As the wavelength separation $\Delta\lambda$ is directly related to the birefringence value, weak birefringence induces small $\Delta\lambda$ value (a few tens or hundreds of pm) compared to the bandwidth of the device (a few or a few tens of nm). Due to this weak $\Delta\lambda$ value, the measurement of the grating group delay τ can correspond to the group delays τ_x or τ_y. Let us consider that $\tau \equiv \tau_y$. This assumption physically involves that the influence of the birefringence can be neglected on the group delay, and consequently on the CD defined by $CD(\lambda) = d\tau / d\lambda$.

While the birefringence does not strongly affect the grating response, its presence leads to DGD. DGD is defined by:

$$\mathrm{DGD}(\lambda) = \left|\tau_x(\lambda) - \tau_y(\lambda)\right| \tag{1}$$

Taking into account previous relationship associated to delays, the DGD can be expressed as

$$\mathrm{DGD}(\lambda) \cong \left|\tau_x(\lambda) - \tau_x(\lambda+\Delta\lambda)\right| \cong \left|\tau(\lambda-\Delta\lambda) - \tau(\lambda)\right| \tag{2}$$

Let us now define a new parameter defined as the ratio between DGD and $\Delta\lambda$:

$$\frac{\mathrm{DGD}(\lambda)}{\Delta\lambda} \cong \frac{\left|\tau(\lambda-\Delta\lambda) - \tau(\lambda)\right|}{\Delta\lambda} \cong \left|\mathrm{CD}(\lambda)\right| \tag{3}$$

Considering the definition of chromatic dispersion, this parameter is an approximation of the absolute value of CD. So, Eq. (3) represents the relationship that exists between DGD and CD for any kind of fibre gratings. It is the generalization of the one presented in [8] for the particular case of chirp Bragg grating.

The $\Delta\lambda$ parameter depends on the birefringence value and the grating pitch Λ: for LPG [9], $\Delta\lambda = \Lambda\,(\Delta n + \Delta n_{cl})$ where Δn and Δn_{cl} represent the birefringence of the guided core and cladding modes, respectively. For FBG [2], $\Delta\lambda = 2\,\Delta n\,\Lambda$. So, the relationship between DGD and CD for LPGs and FBGs are respectively given by:

$$\mathrm{DGD}(\lambda) \cong \Delta\lambda \,.\, |\mathrm{CD}(\lambda)| \cong (\Delta n + \Delta n_{cl})\,\Lambda \,.\, |\mathrm{CD}(\lambda)| \tag{4}$$

$$\mathrm{DGD}(\lambda) \cong \Delta\lambda \,.\, |\mathrm{CD}(\lambda)| \cong 2\,\Delta n\,\Lambda \,.\, |\mathrm{CD}(\lambda)| \tag{5}$$

Eq. (4) and (5) show that the wavelength dependency of grating DGD depends on the CD evolution with wavelength, the birefringence and the grating pitch Λ. Since $\Delta\lambda$ is not wavelength dependent, we can conclude that the shapes of DGD and CD evolutions with wavelength are the same. Moreover, Λ is a constant parameter well known by the manufacturing process (precision < 0.1 %) such as grating DGD is only dependent on the CD evolution with wavelength and the birefringence. Since the grating CD depends on the grating physical parameters (core refractive index modulation amplitude and profile, grating length) and, as previously mentioned, it does not depend on the birefringence for weakly birefringent gratings, we can state that the grating DGD evolution is separately affected by the birefringence and by the grating physical parameters through the CD.

This relationship between CD and DGD can be used to characterize the grating birefringence. Since DGD is separately affected by the grating birefringence and the grating physical parameters through CD parameter, the comparison between experimental DGD and CD evolutions leads to the birefringence value. Since it is based on two grating responses measurements, this reconstruction method of the birefringence value does not require to know the grating parameters (such as the core refractive index modulation amplitude and profile and the grating length), which constitutes a real advantage compared to the technique presented in [2].

Experimental demonstrations of the derived relationship are reported below for two cases of gratings exhibiting birefringence. The first is conducted on an LPG exhibiting birefringence induced by mechanical stress. For the second, we used an FBG exhibiting mainly photo-induced birefringence.

Our LPG was written into hydrogen-loaded standard single mode fibre by means of a frequency-doubled argon-ion laser at 244 nm. The grating period of 475 µm has been chosen to obtain a resonance in the C+L transmission band. The grating length was 2.85 cm. The writing process lasted 7 minutes with a mean UV power equal to 76 mW. After the manufacturing process, the grating was annealing at 100°C during 16 hours in order to stabilize its properties. The amplitude transmission response in the C+L band is plotted in the inset in Fig. 1 (a) (solid curve). The chromatic dispersion was obtained by using the phase-shift technique. The experimental result is depicted in Fig. 1 (a). After exposure, our LPG does not exhibit significant birefringence value so that there are practically no measurable DGD values. Birefringence was therefore mechanically induced by applying a transversal force to the LPG. Care was taken to obtain a uniform birefringence along the grating.

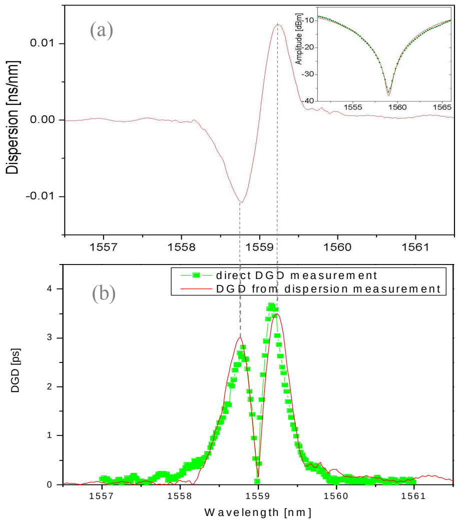

Fig. 1. LPG chromatic dispersion (a) and DGD (b); amplitude response (in the inset in (a)).

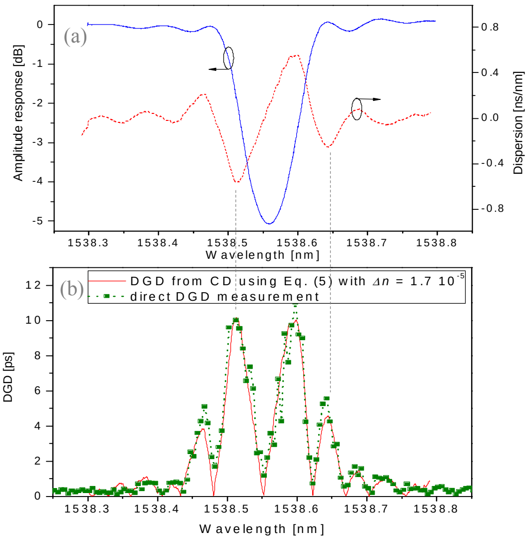

Fig. 2. FBG response: amplitude and CD (a) and DGD (b)

The amplitude transmission response of our birefringent LPG is also depicted in the inset in Fig. 1 (a) (dotted line). As observed, while the imposed birefringence leads to important DGD (see below), it does not significantly affect the LPG amplitude response. These experimental conditions agree with our assumption previously mentioned. The DGD evolution with wavelength was obtained by measuring the Jones matrix of the grating in transmission versus wavelength (Jones matrices eigenanalyzis method [10]) using a tunable laser source and a polarimeter. During measurements, all the fibres were fixed to avoid polarization instabilities. The experimental result for the wavelength evolution of DGD is depicted in Fig. 1 (b) (dotted line). In addition, we plotted on Fig.1 (b) (solid line) the DGD curve derived from CD measurement using Eq. (4) by adjusting the $\Delta\lambda$ factor. The best fit was obtained for $\Delta\lambda$ equal to 280 pm (that gives 5.9 10^{-7} for the sum of the core and the cladding birefringence).

A second experiment was conducted on a uniform Bragg grating written into boron co-doped photosensitive fibre. This type of fibre possesses a greater propensity to induce birefringence during the writing process. We used the continuous grating writing technique and the interference pattern was created by a 1060 nm period phase mask (giving Λ = 530 nm). Evolution with wavelength of CD is depicted in Fig. 2 (a) where the amplitude transmission is also presented. The experimental DGD result is depicted in Fig. 2 (b) (dotted line). It agrees with the theoretical DGD evolutions of FBGs [2]. In Fig. 2 (b) (solid curve), we present in addition the DGD curve derived from CD using Eq. (5) with Λ = 530 nm. A birefringence equal to 1.7 10^{-5} gives the best fit between the two experimental results. It well corresponds to the value obtained from the technique using the comparison between simulated and experimental DGD evolutions [2].

As a conclusion, we theoretically demonstrated that the wavelength dependencies of the absolute value of CD and DGD in weakly birefringent gratings are correlated: they only differ in amplitude by a constant factor depending on the birefringence. We explained how the relationship between DGD and CD can be exploited to get the grating birefringence. Measurements conducted on two different birefringent gratings experimentally demonstrated the validity of the derived relationship: in both cases, the wavelength dependency of DGD corresponded to the CD evolution with wavelength weighted by the birefringence. In addition, the CD and DGD experimental evolutions were used to get the grating birefringence.

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