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MEASUREMENT AND ANALYSIS OF PMD IN SPUN FIBRES WITH DIFFERENT LINEAR BIREFRINGENCE AND SPINNING PARAMETERS

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Abstract: We show how the intrinsic linear birefringence determines the necessary spinning parameters to produce spun fibre with optimum differential group delay (DGD) and polarisation mode dispersion (PMD) properties. We believe these are the first reported simulation and experimental results showing the DGD reduction in such spun fibres for different spin parameters.

Introduction: It is only recently that spun fibre has become available commercially. These fibres are produced not by spinning the preform uniformly while the fibre is being drawn, as was originally suggested [1], but by applying a sinusoidally varying torque to the fibre being drawn, alternatively in the clockwise and counter-clockwise directions. The DGD of the resultant fibre is then determined by three parameters namely, the starting linear birefringence of the fibre, the spin rate and spin period of the alternating spinning process. We have carried out a detailed analysis of how the joint interactive effect of these three parameters determines firstly, the intrinsic DGD of the resultant fibre when no external twist is applied to it, and secondly, how this zero twist DGD value changes when the fibre is subjected to external twist. Whereas the reduction of the starting DGD in a uniformly spun fibre, and its reduction with external twist, can be calculated in an exactly analytical form [2], for fibres produced using an alternating spin process we have numerically simulated the starting DGD, and its change with twist, and there is good agreement between our simulation and experimental results. We believe these to be the first such results to be reported and that they provide valuable guidance on the choice of the parameters associated with the manufacturing processes in order to produce a well behaved low PMD fibre.

Theoretical Model: In a spun fibre with starting linear birefringence $\delta\beta_L$, sinusoidal spin $\tilde{\alpha}_\gamma$ and externally applied twist γ the local birefringence vector can be written following [2, 3], as

$$\delta\vec{\beta}(l) = \begin{pmatrix} \delta\beta_L \cos(2\tilde{\alpha}_\gamma + 2\gamma l) \\ \delta\beta_L \sin(2\tilde{\alpha}_\gamma + 2\gamma l) \\ g\gamma \end{pmatrix} \tag{1}$$

with

$$\tilde{\alpha}_\gamma = A_\gamma \sin\left(2\pi\kappa_\gamma l\right) \qquad \left(rad\right) \tag{2}$$

where l is the distance along the fibre, g is the rotation coefficient, A_γ is the amplitude of the applied twist in radians and κ_γ the spatial frequency in cycles/m which can also be expressed by the spatial period $\Lambda_\gamma = 1/\kappa_\gamma$ with units in metres. By taking the derivative of Equation (2), with respect to the fibre length l, $\tilde{\gamma}_{rms}$, the root mean square value of $d\tilde{\alpha}_\gamma/dl$, which we define as the effective spin rate with units (rad/m), can be expressed as

$$\tilde{\gamma}_{rms} = \frac{2\pi}{\sqrt{2}} \frac{A_\gamma}{\Lambda_\gamma} \qquad \left(rad/m\right) \tag{3}$$

The local SOP in the spun fibre can be mathematically expressed as a rotation around the resultant local birefringence vector $\delta\vec{\beta}$ by the following differential vector equation [4, 5]

$$\frac{d\vec{\mathbf{s}}(l,\omega)}{dl} = \delta\vec{\beta}(l,\omega) \times \vec{\mathbf{s}}(l,\omega) \qquad (4)$$

Equation (4) consists of three first order coupled differential equation which can be solved by numerical integration. From the computed SOP at three different wavelengths by considering the wavelength dependence of g and $\delta\beta_L$ [2] the DGD can be calculated from the rotation of the SOP on the Poincaré sphere as a function of wavelength [4].

Measurement: The DGD versus external twist has been measured, using Jones matrix eigenanalysis, for four different free hanging fibres of length $l \approx 114$ m and the results are shown in Fig. 1 and Fig. 2. The fibres are two dispersion shifted fibres (DSF 1 and 2) and two spun DSFs (DSF Spun 1 and 2), DSF 1 and DSF Spun 1 were made from the same preform, and DSF 2 and DSF Spun 2 from another. It can be clearly seen in Fig. 1(b) that at zero twist DSF 2 has a DGD value nearly twice that of DSF 1 in Fig. 1(a), implying higher (~ double) linear birefringence in DSF 2. This difference in linear birefringence has a significant influence on the performance of the spun fibre made from these two preforms. In Fig. 2(a) one can see that DSF Spun 1, which has the same parent preform as DSF 1, has a virtually zero DGD at zero twist, and its DGD grows nearly linearly with twist. However, DSF Spun 2 behaves very differently from DSF Spun 1 in that the DGD around zero twist fluctuates significantly with twist, and the peaks are up to half the DGD value of DSF 2 at zero twist. From the system application point of view this type of DGD fluctuation versus twist is highly undesirable, because in the process of cabling and cable laying some twisting is often unavoidable.

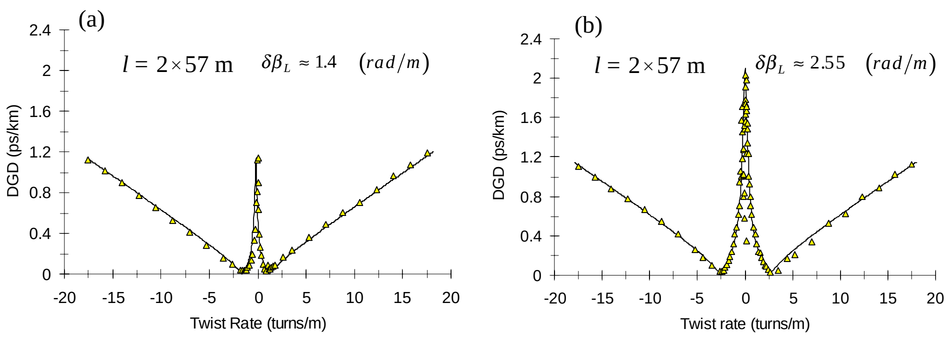

Fig. 1 Measured and calculated values of DGD against twist. In (a) for DSF 1 and in (b) DSF 2.

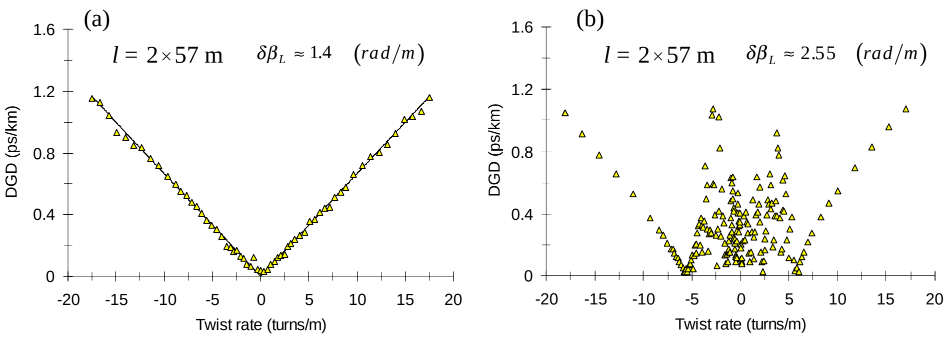

Fig. 2 Measured values of DGD against twist. In (a) for DSF Spun 1 and in (b) for DSF Spun 2.

Simulation: In order to understand the different behaviours of DSF Spun 1 and 2 numerical simulations were carried out. The intrinsic linear birefringence of DSF Spun 1 and 2 has been estimated from DSF 1 and 2, which have the same parent preform respectively, by using $\delta\beta_L \approx \omega \bullet$ DGD at λ = 1. 55 μm (which neglects the wavelength dependence of the mode field [2]) to be $\delta\beta_L$ = 1.4 and 2.55 rad/m respectively. This was then fed into the simulation program as the intrinsic linear birefringence values for DSF Spun 1 and 2 and the DGD versus twist was simulated with different internal spin amplitudes and periods, assuming that the fibre has a sinusoidal spin style. In Fig. 3(a) and (b) the effective spin $\tilde{\gamma}_{rms}$ has been chosen as 1.1 and 4.4 turns/m for the simulation of the DGD versus twist of DSF Spun 2. It can be seen in Fig. 3 (a) and (b) that the effective spin is not large enough to zero the starting DGD at and around zero external twist. Fig. 3(b), for the chosen effective spin, shows an interesting similarity to the measured DSF Spun 2 case in Fig. 2(b) in the way the DGD evolves with external twist. However the peak to peak value of the DGD fluctuation versus twist in Fig. 2(b) is far higher than the one predicted by the simulation in Fig. 3(b). This could be due to the fact that in the measured fibre the twist in the two fibre sections (The 114 m length was folded in two over a pulley) have slightly different magnitudes. The simulation results of such spun fibre with different fibre lengths showed that this fluctuation grows linearly with length, confirming also the normalisation in (ps/km) as done in the figures. For the higher effective spin values of 8.9 and 17.8 turns/m, as shown in Fig. 4 (a) and (b), the DSF Spun 2 starts now to behave, in its DGD versus twist, as we would expect for such a spun fibre with overall DGD close to zero at zero twist, indicating that the effective spin in this fibre is now large enough.

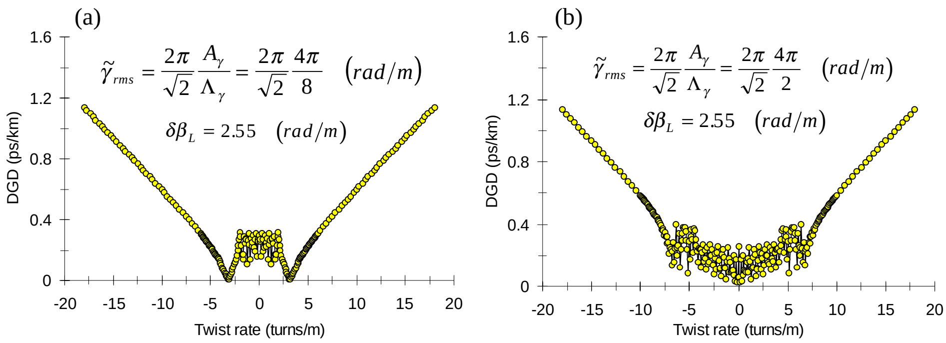

Fig. 3 Numerical calculation of DGD versus external applied twist for DSF Spun 2. In (a) for $\tilde{\gamma}_{rms} \approx$ 1.1 turns/m and in (b) for $\tilde{\gamma}_{rms} \approx$ 4.4 turns/m.

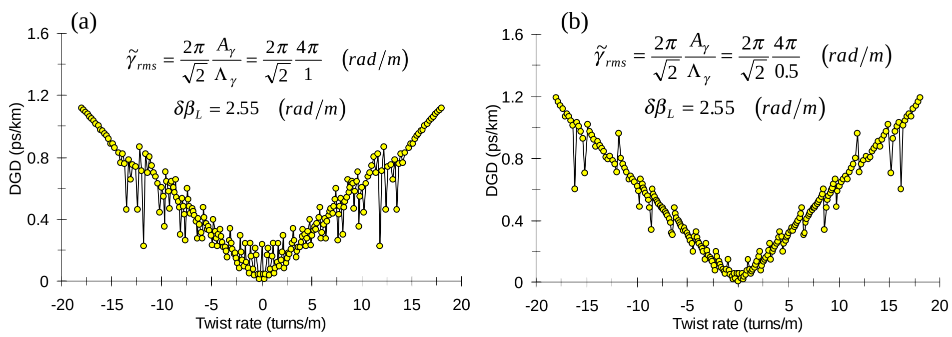

Fig. 4 Numerical calculation of DGD versus external applied twist for DSF Spun 2. In (a) for $\tilde{\gamma}_{rms} \approx$ 8.9 turns/m and in (b) for $\tilde{\gamma}_{rms} \approx$ 17.8 turns/m.

In Fig. 5 (a) and (b) the simulation results are shown for DSF Spun 1 with $\delta\beta_L$ = 1.4 rad/m and using an effective spin of 1.1 and 4.4 turns/m as used for DSF Spun 2 in Fig. 3 (a) and (b) respectively. It can be seen in Fig. 5 (a) that the effective spin of 1.1 turns/m seems not to be large enough to obtain a zero overall DGD at and around zero external twist. However for

$\tilde{\gamma}_{rms}$ = 4.4 turns/m, Fig. 5 (b), DSF Spun 1 shows, even at this 'low' spin rate (compared with DSF Spun 2), a DGD versus external twist behaviour which is approaching that measured on DSF Spun 1, as shown in Fig. 2(a), and which represents a well behaved spun fibre.

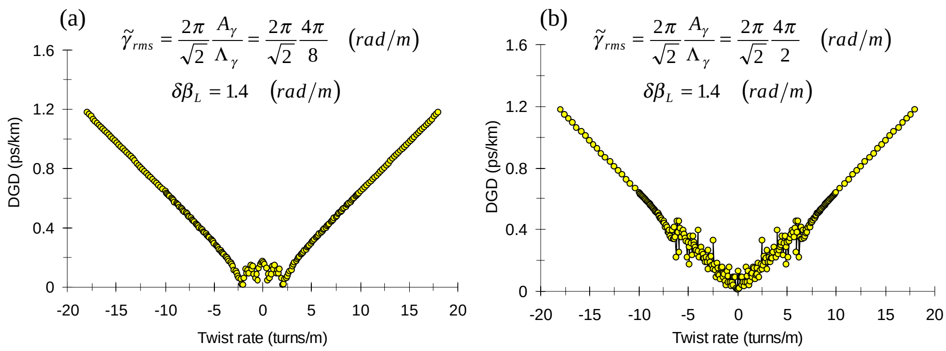

Fig. 5 Numerical calculation of DGD versus external applied twist for DSF Spun 1 In (a) for $\tilde{\gamma}_{rms} \approx 1.1$ turns/m and in (b) for $\tilde{\gamma}_{rms} \approx 4.4$ turns/m.

Discussion: When subjected to an external twist, spun fibre with a sinusoidal spin should show, if the internal spin rate is high enough, a uniform increase in DGD as if the fibre did not possess any internal linear birefringence. Our range of simulations show that to achieve sufficient DGD reduction in such fibres, an empirical value for the minimum spin needed may be obtained in terms of the fibre linear birefringence by

$$\tilde{\gamma}_{rms} > 4 \cdot \delta\beta_L \qquad (turns/m) \tag{5}$$

Conclusions: We have measured and numerically simulated sinusoidally spun DSF, and have found that, for a fibre with a given starting linear birefringence, there exists a minimum spin rate for effective DGD reduction in the spun fibre. If the spin is not high enough so that the starting DGD is not reduced sufficiently, peaks up to half the height of the starting DGD can occur, which could result in a higher PMD in an overall link.

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