MEASUREMENT OF SOP EVOLUTION ALONG A LINEAR BIREFRINGENT FIBRE WITH TWIST USING POLARISATION OTDR

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Abstract: We show how the state of polarisation (SOP) evolution along optical fibres can be measured using the non-destructive method of polarisation optical time domain reflectometry (POTDR). From the SOP evolution the linear birefringence and twist can be calculated along the fibre, thus identifying fibre sections with and without twist and sections with relatively high and low polarisation mode dispersion (PMD).

Introduction: POTDR, like OTDR, is a non-destructive method for measuring fibre parameters such as the birefringence characteristics [1] along the fibre with access to only one end. If the linear and circular birefringence distribution along a fibre is known, the fibre can be modelled. This would allow not just the PMD of the fibre to be calculated [2] but, as we show in this paper, also fibre sections with and without twist to be identified.
The POTDR fluctuation is a complicated function of the linear-circular birefringence distribution along the fibre. We recently showed that fibre twist significantly influences the periodicity of the observed signal from POTDR, and has to be taken into account when estimating PMD using this technique [3, 4]. In this paper we report a further result, namely that the SOP evolution obtained from a POTDR can be used to give the polarisation properties of the fibre. We believe this is the first report of experimental POTDR results showing the SOP evolution on the Poincaré sphere along a fibre with twist.

Theoretical Model: In [3, 4] it was shown that $\overleftarrow{\mathbf{S}}(l)$, the SOP observed at the input end of the fibre from the backscattered signal at the length l, along a uniformly twisted fibre, can be expressed as

$$\overleftarrow{\mathbf{S}}(l) = \mathbf{R}^T(\vec{\beta} l)\mathbf{A}_M \mathbf{R}(\vec{\beta} l)\vec{\mathbf{S}}(0) = \mathbf{M}(\vec{\beta} l)\vec{\mathbf{S}}(0) \qquad (1)$$

where $\mathbf{A}_M$ is the rotation invariant mirror matrix which changes the handedness of the SOP and $\mathbf{R}^T$ is the transpose of a rotation $\mathbf{R}$, given by

$$\mathbf{R} = \mathbf{I} + \sin(\beta l)\mathbf{B} + \left(1 - \cos(\beta l)\right)\mathbf{B}^2 \qquad (2)$$

where $\mathbf{I}$ is the 3x3 unit matrix, $\mathbf{B}_{ij} = \sum_{k=1}^{3} \varepsilon_{ijk}\hat{\beta}_k$ is a skew-symmetric matrix where ε_{ijk} is the permutation symbol which is 1 for cyclic, -1 for non-cyclic permutation of indices 1, 2, 3, and the unit vector $\hat{\beta}$ is determined in the rotating reference frame as $\hat{\beta} = \left(\beta_L \quad 0 \quad 2\gamma - g\gamma\right)^T \big/ \beta$. Here, the magnitude, $\beta = \sqrt{\beta_L^2 + \left(2\gamma - g\gamma\right)^2}$ is the resultant birefringence due to the linear birefringence, β_L, the twist rate, γ, and the rotation coefficient, g. The occurrence of the rotation matrix $\mathbf{R}$ twice in Eq. 1 indicates that the matrix coefficients of $\mathbf{M}$ are quadratic in $\cos(\beta l)$ and $\sin(\beta l)$ and in general the intensity through an analyser may be expressed in the form of a Fourier series

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$$I = a_0 + \sum_{n=1}^{2} a_n \cos(n\beta l) + b_n \sin(n\beta l) \qquad (3)$$

In the general case the evolution of the backscattered SOP is a self intersecting 'figure of eight' whose detailed shape depends on the incident SOP, linear birefringence and twist induced circular birefringence. For the simple case of zero twist the SOP trace is just a circle, a_1 and b_1 being zero, leading to just one component in the POTDR power spectrum. For backreflection from a section with twist, a_1 and b_1 are now not zero which, together with a_2 and b_2, lead to two components in the POTDR spectrum. This qualitative difference between the two POTDR spectra makes it possible to detect sections of fibre with twist. Measurement with simulation results using the power spectrum with the two frequencies will be presented. In this summary we show the full SOP evolution along the fibre obtained from POTDR.

Equation 1 may be extended to the SOP evolution as measured with the POTDR set-up shown in Fig. 1 by multiplying the backscattered SOP, $\overleftarrow{\mathbf{S}}(l)$, with a constant rotation matrix, $\mathbf{R}_C$ which is the transmission matrix of the 3dB coupler in backward direction, so that

$$\overleftarrow{\mathbf{S}}(l) = \mathbf{R}_C \mathbf{M}(\vec{\beta} l)\vec{\mathbf{S}}(0) \qquad (4)$$

$\mathbf{R}_C$ is just an overall rotation of the backscattered SOP trace on the Poincaré sphere.

Results and Discussion: A commercially available OTDR, with a spatial resolution of 2m, was modified with a computer controlled rotatable λ/4 waveplate-linear polariser combination, Fig. 1. A 56m length of fibre was freely suspended from either end, and twisted at the far end. The zero twist condition could be found by measuring the PMD at different twist rates [4]. The SOP from the backscattered intensity can be calculated by rotating the λ/4 plate to at least four independent positions. In our experiment we used 19 analyser positions from 0 to 180 degree for calculating the backscattered SOP, using a least square method. The SOP data was very reproducible over repeated measurements. Due to the dead zones at either end only 50 metres of the fibre could be resolved with our POTDR setup.

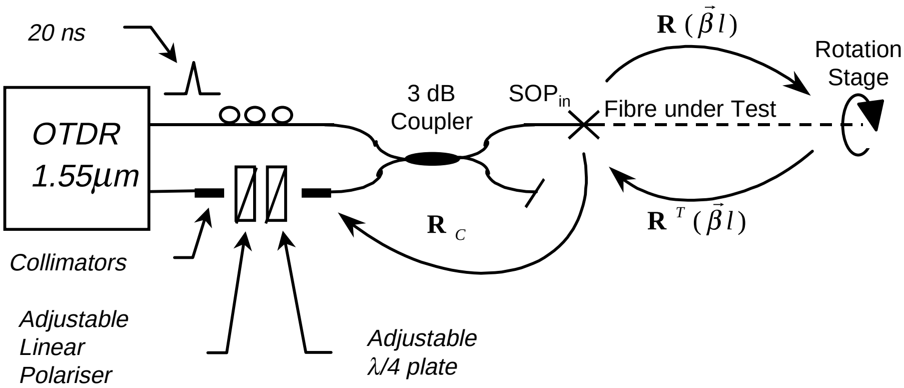

Fig. 1 Experimental POTDR setup.

Fig. 2(a-e) shows the measurement and best fit simulation results at different twist rates for the backscattered SOP. The simulation is fitted to the measurements interactively on both the Poincaré sphere and on the azimuth and ellipticity variation of the SOP as a direct function of length using Eq. 4. Figure 2(a) shows the SOP evolution on the Poincaré sphere for the fibre in the zero twist condition, defined as

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that giving maximum PMD [4]. Now if the zero twist condition actually existed over the whole length of the fibre then the SOP trace would be just a repeated circle. However in the data of Fig. 2(a) only the last 31 metres of the fibre shows a repeated circular trace on the Poincaré sphere, the first 19 metres giving data points away from the circle. From this, and measuring the fibre with left and right hand twist using the POTDR, we could conclude that the first 19 metres of fibre has some small non-uniform linear birefringence and twist which may be frozen in during the fibre fabrication process. The last 31 metres of fibre was then modelled as a section with a nominally constant linear birefringence as the variable, to find the best fit to the measurements. The best fit simulation, indicated in Fig. 2(a), was obtained for β_L = 0.19rad/m for the last 31 metres of fibre. This value is within 34% of a value obtained by a direct PMD measurement over the whole 56 metre length of the fibre.

In Fig. 2(b-e) we again carry out the simulation for the last 31 metre section of the fibre. Applying a twist of 0.01 turns/m, Fig. 2(b), the backscattered SOP traces a figure of eight shape in accordance with Eq. 2 and 4. For the higher applied twist rate of 0.019 turns/m, Fig. 2(c), the area of the figure of eight decreases as predicted in [3, 4]. The simulated traces for the two applied twist rates, Fig. 2(b-e), again give β_L = 0.19rad/m and twist values of 0.012 and 0.021 turns/m respectively for the best fit. Fig. 2(d-e) show the azimuth and ellipticity variation of the SOP evolution for the applied twist of 0.019 turns/m as a function of length, where L = $2\pi/\beta$ is the input SOP independent periodicity of the traces. Applying twist in the opposite direction also gave a figure of eight in the SOP evolution but with opposite direction as expected.

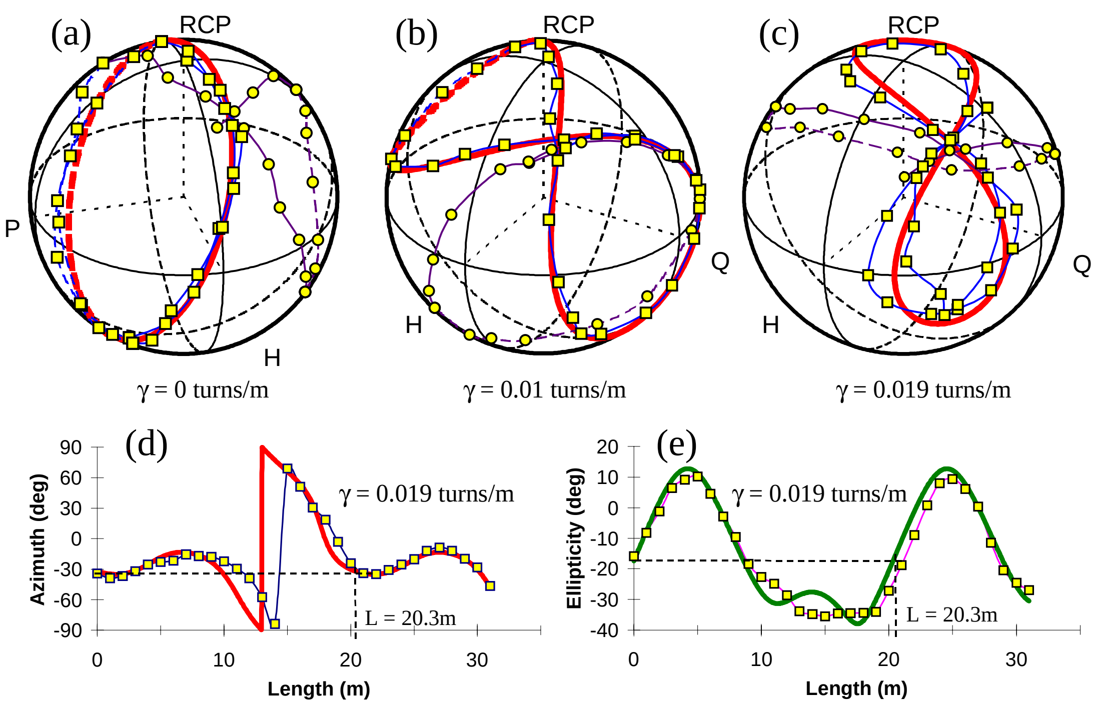

Fig. 2(a-e) Measurement and simulation of the SOP evolution along fibre with different twist rates using a POTDR.

Measurement from first 19m
Measurement from last 31m
Simulation

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Conclusions: The SOP evolution along a fibre has been measured using POTDR and plotted on the Poincaré sphere. It has been shown that the linear birefringence and twist along the fibre can be evaluated using this data. Knowing the twist and linear birefringence along the fibre the PMD of the fibre can be calculated. This may be used during the manufacture of the fibre at different production stages to monitor the intrinsic PMD expectation of the fibre.

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