ANISOTROPY IN SPUN SINGLE-MODE FIBRES

Indexing terms: Optical fibres, Birefringence

It is shown that the dominant process for the reduction of birefringence in a spun fibre is the averaging of the local fibre anisotropy by the rapid procession of the axes of asymmetry along the fibre. No significant change in cross-sectional geometry occurs.

Introduction: Single-mode optical fibres which exhibit very low polarisation birefringence are essential for optimal sensitivity of the Faraday current monitor[1] and other polarimetric sensor devices.[2] Furthermore, the low-polarisation mode dispersion present in such fibres is advantageous for high-bandwidth long-distance communications.[3]

Birefringence arises intrinsically within a fibre from the combined effects of core ellipticity (shape birefringence) and asymmetric thermal stress-birefringence.[4] Two methods exist for the fabrication of fibres with negligible levels of birefringence. In the conventional approach, attempts to carefully maintain the circular geometry and match the thermal expansion within the preform during fabrication have yielded a fibre with a birefringence of only 2·6 deg/m,[4] although this level is difficult to achieve reproducibly. A new approach,[5,6] is to spin the preform during fibre drawing with the result that dramatically low birefringence fibres can be consistently produced.

It is thought that the preform spinning process produces a simple frozen-in twist of the axes of asymmetry of the fibre, and this can be shown theoretically[7] to produce low birefringence on a macroscopic scale by averaging the propagation constants of the two orthogonally-polarised fibre modes. Thus the fibre may still have high local birefringence. However, it has been suggested that spinning the preform may also serve to smooth out and reduce the asymmetry in the molten preform tip during drawing. This would give rise to a low birefringence, not only on a macroscopic scale but also on a local scale within the fibre.

In this letter, we show conclusively that there is insignificant modification of the local anisotropy, and that it is indeed the rapid precession of the axes of asymmetry which is the dominant mechanism for producing low overall birefringence in a spun fibre. We do this by untwisting the fibre after drawing, and demonstrate that the linear birefringence reappears at a point when the applied twist cancels that frozen-in during drawing. Furthermore, by this technique it is possible to determine the intrinsic birefringence $\delta\beta$ present before spinning, as well as the spin pitch of the fibre.

Theory: The variation of macroscopic retardation with additional applied twist in a spun fibre can be calculated by first representing the spun fibre as a twisted fibre with zero induced photoelastic rotation.[7] This is valid, as at typical fibre-drawing temperatures the hot zone is fluid and cannot support significant torsional stresses; thus the twist is permanently frozen in. The twist applied after drawing then acts as an additional twist but, in contrast, has an associated photo-elastic rotation given by $g'\xi$,[8] where $g' \simeq 0{\cdot}073$,[7] and ξ is the applied twist rate (deg/m). We obtain the retardation $R(z)$ in a fibre of length z from Reference 7 as

$$R(z) = 2 \sin^{-1}\left\{\frac{1}{(1+q^2)^{1/2}} \sin \gamma z\right\} \qquad (1)$$

where

$$q = \frac{2\{\xi(1-g') + \xi_1\}}{\delta\beta} \qquad (2)$$

and

$$\gamma = \tfrac{1}{2}[\delta\beta^2 + 4\{\xi(1-g') + \xi_1\}^2]^{1/2} \qquad (3)$$

Here, $\delta\beta$ is the intrinsic birefringence in the unspun fibre and ξ_1 the fibre spin rate in deg/m. Our sign convention is such that ξ_1 is negative.

Fig. 1 shows the macroscopic retardation, predicted by eqn. 1 as a function of the applied twist for a fibre of length 1·262 m, $\delta\beta$ (633 nm) = 14·42 deg/m and a spin pitch $P = 2\pi/\xi_1 =$ 5·24 cm. We see that when the twist counteracts the spin, the spin-averaging effect is progressively reduced, and the intrinsic local birefringence consequently becomes more apparent. The overall birefringence rises and peaks at a twist rate ξ given by

$$\xi(1-g') = -\xi_1 \qquad (4)$$

At this point the applied twist is such that the induced rotation is equal to the remaining twist $(\xi + \xi_1)z$ in the fibre. Thus the plane of polarisation of the light rotates to follow the residual twist; light polarised along the local principal axes at the input remains oriented parallel to the (rotating) local axes along the entire fibre length. Effectively, then, the local axes are 'aligned' to the linearly-polarised light and the fibre exhibits the full retardation $\delta\beta$, with, in addition, a net rotation of $g'\xi z$. Increasing the twist beyond this birefringence peak results in a return to negligible levels of retardation, as in a highly-twisted fibre. Note that when the twist acts in the same sense as the spin (i.e. ξ negative), the retardation remains negligibly small for all applied twist rates.

Experiment and discussion: The linear birefringence in a silicone-coated spun fibre was measured at 633 nm as a function of applied twist using a polariser and analyser. The fibre had a nominal spin pitch of ~ 5 cm, a length of 1·262 m and was hung vertically to ensure elimination of residual twist and a uniform applied twist rate. The results are superimposed on Fig. 1, and are seen to be in excellent agreement with the prediction of eqn. 1, when appropriate values for $\delta\beta$ and ξ_1 are chosen.

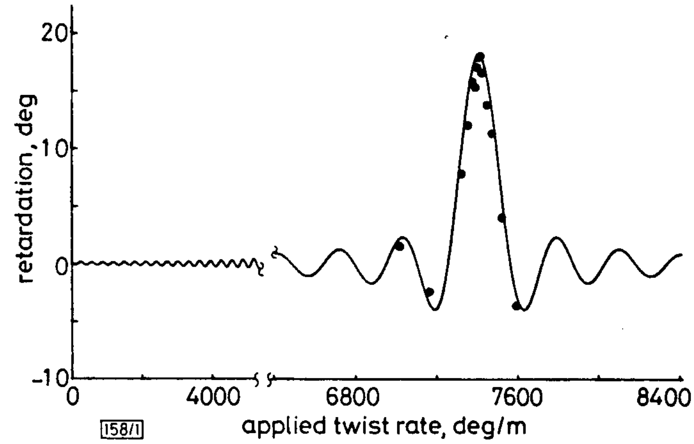

Fig. 1 *Measured retardation at 633 nm as function of applied twist rate for 1·262 m length of spun fibre with nominal spin pitch of ~5 cm*

Solid line is theoretical prediction of eqn. 1, with $2\pi/\xi_1 = 5{\cdot}24$ cm and $\delta\beta = 14{\cdot}42$ °/m

The peak measured retardation of 14·42 deg/m corresponds to the local birefringence $\delta\beta$ in the spun fibre, and compares well with the value of $\delta\beta = 32$ deg/m measured in an unspun

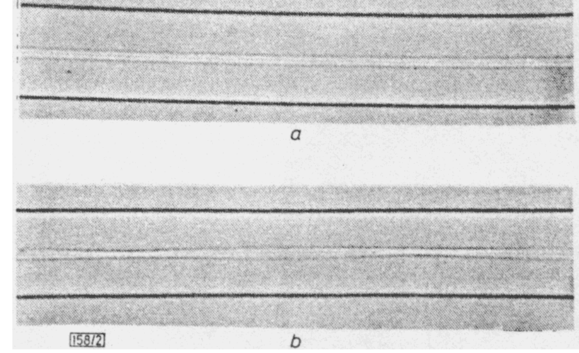

Fig. 2 *Comparison of transverse sections of highly elliptical fibre*

a Unspun

b Spun with a spin pitch of ~ 1·2 mm, showing spiralling elliptical core and cladding section 100 m down the fibre. The agreement is within the normally expected variation of intrinsic birefringence along the fibre length.

From the twist required to achieve peak retardation we can estimate the spin pitch using eqn. 4. In the example shown in Fig. 1 the spin pitch P of the fibre was calculated to be 5·24 cm. This value compares well with the nominal value of 5·0 cm, and is within the calibration error of the preform-spinning-motor speed control. For this experiment a knowledge of the nominal spin pitch of the fibre in question is essential, since the range of twist over which the retardation reappears is very narrow (Fig. 1).

The close agreement between the nominal and measured spin pitches suggests that the viscosity of the glass in the drawing-furnace hot zone is sufficiently low to allow complete relaxation of torsion by viscous flow. This was verified by using an as-drawn 10 m length of spun fibre which had been constrained from untwisting after drawing by winding directly onto a drum. No significant untwisting of a marker on the end of the fibre was observed when the fibre was paid off the drum and allowed to hang free vertically.

The reappearance of the birefringence with applied twist confirms that a spun fibre retains a large local anisotropy with a value approximately equal to the intrinsic fibre birefringence $\delta\beta$ before spinning. Thus the spinning process would not appear to circularise the geometry or reduce the stress anisotropy significantly. Further confirmation of this is provided by Figs. 2*a* and *b*, where the transverse-sections of unspun and spun lengths of the same highly-elliptical fibre are compared.

Fig. 2*b* clearly shows the elliptical core and cladding spiralling along the spun fibre. Spinning evidently produces little change of the cross-sectional geometry of the fibre. The unspun fibre had a high birefringence (beat length $2\pi/\delta\beta = 19$ mm) arising largely from its major : minor axis ratio of $\sim 2{\cdot}5$: 1. However, the spun fibre (spin pitch $P \simeq 1{\cdot}2$ mm) exhibited birefringence, as expected when the spin rate far exceeds the initial birefringence.[5,7,8]

Conclusion: It has been shown that the reduction in birefringence of a spun fibre can be attributed largely to the averaging effect of the precession of the fibre axes of asymmetry and not to changes in cross-sectional geometry or smoothing of anisotropic stress. By applying a reverse twist, the spin averaging effect can be reduced. At a twist rate which compensates for the intrinsic spin the full intrinsic birefringence $\delta\beta$ can be made to reappear by effectively aligning the local birefringence axes. The effect allows the determination of both the intrinsic unspun fibre birefringence $\delta\beta$ and the fibre spin pitch P from the peak in the spun fibre retardation against applied reverse twist. The reappearance of the birefringence with applied twist is an important feature of a spun fibre and could possibly be exploited in a fibre-angle sensor.

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A. J. BARLOW *21st January 1982*
J. J. RAMSKOV-HANSEN
D. N. PAYNE

Department of Electronics
University of Southampton, Hants. S09 5NH, England

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