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ENHANCEMENT OF BIREFRINGENCE IN POLARISATION-MAINTAINING FIBRES BY THERMAL ANNEALING

Indexing terms: Optical fibres, Birefringence

The thermal behaviour of highly birefringent polarisation-maintaining optical fibres is studied, and the thermal hysteresis of the birefringence is related to the quenching of the fibre. Suitable 'on-line' thermal annealing during fibre drawing is shown to be a method for the full development of the high anisotropic stresses potentially available in high birefringence structures using borosilicate stress-producing parts.

Introduction: Highly birefringent fibres attempt to overcome the effect of perturbations, for example, bends and twists by deliberately introducing levels of birefringence in excess of that produced by external factors, thereby rendering the output polarisation state relatively immune to all but the most major disturbances. Such fibres are characterised by their birefringence B, defined as $n_x - n_y = \Delta\beta(\lambda/2\pi)$, where n_x and n_y refer to the refractive indices for light polarised along the fibre principal axes x and y, respectively. A commonly quoted figure of merit is the so-called beat length $L_p = \lambda/B$ and it is desirable to achieve the smallest possible beat length to ensure lack of sensitivity to external perturbations.

Very small values of beat length[1] can be obtained by using the anisotropic thermal stress produced by incorporating high-expansion doped regions within the fibre. A variety of such structures have been reported in the literature.[1-3] The smallest values of beat length (highest birefringence) reported to date have been achieved in our laboratory by means of the so-called 'bow-tie' side-pit structure; beat lengths of 0·55 mm at a wavelength of 633 nm have been successfully produced.

The temperature-dependent behaviour of a number of elliptically clad high-birefringence fibres was studied in Reference 3, where a thermal hysteresis of the beat length was reported. However, no firm conclusions were reached regarding the origin of the effect, and it was found that the improvements in birefringence obtained by thermal cycling decayed in a matter of days. We report here a simple heat-treatment cycle whereby substantial and stable improvements in beat length can be obtained. The technique has also been applied during the fibre drawing process.

Experimental: In order to determine the thermal behaviour of the birefringence, linearly polarised light ($\lambda = 633$ nm) was launched into the test fibre at 45° to the principal axes, with most of the fibre enclosed in a furnace consisting of a small silica tube and resistance wire wrapping. A photoelastic modulator was used to yield sin Δ and cos Δ of the output light, where Δ is the retardance (see, for example, Reference 4). The charge in Δ, uniquely determined by the combination of sin Δ and cos Δ, was recorded as a function of temperature and time in order to monitor the fibre birefringence, or equivalently, beat length. The use of the photoelastic modulator provides an exceedingly sensitive and fast means of monitoring the fibre birefringence.[4]

'On-line' annealing was achieved by pulling the fibre from the preform in the normal way, but passing it through a four-zone annealing furnace prior to winding the fibre on the drum. The total length of the furnace was 1 m, and the zone temperatures were 550°C, 500°C, 450°C and 400°C, with the fibre entering the hottest zone first. The fibre was effectively at room temperature on entering the annealing furnace. The normal silicone elastomeric coating was found to survive the anneal satisfactorily, but allowance had to be made for its thermal conductivity. The plot of Fig. 3 refers to an uncoated fibre.

Results: Fig. 1 shows the cross-section of a bow-tie fibre manufactured in our laboratory. The boron-doped 'side-pit' regions producing the stress are clearly visible. Fig. 2 is a plot of the relative change in the beat length L_p as a function of temperature, obtained by monitoring the retardance for a length of test fibre using the photoelastic modulator (see above). Curve (*a*) shows the behaviour of the 'as-received' fibre

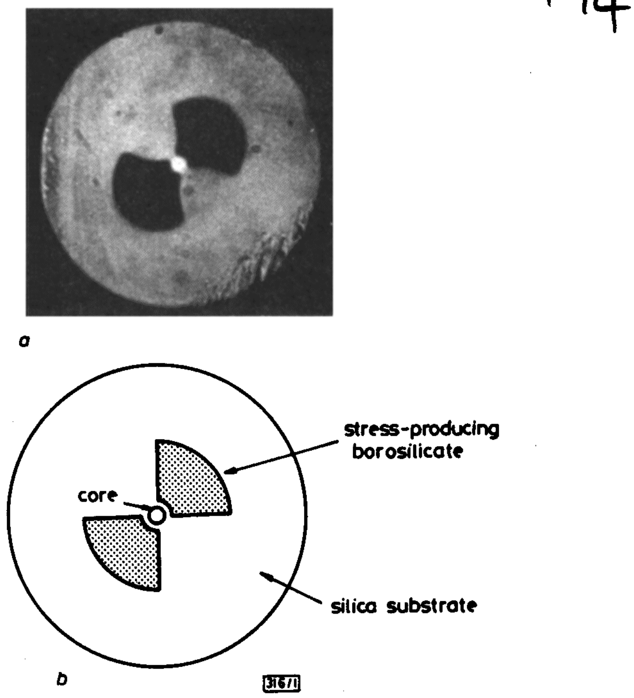

Fig. 1 *Micrograph (a) and sketch (b) of the cross-sectional structure of the bow-tie fibre*

upon heating. Initially an increase in the beat length occurs, which is expected, since the differential contraction of the bow-tie sections and hence the internal stress anisotropy, i.e. the net thermal stress, decreases. Subsequently the beat length undergoes a dramatic reduction, indicating an increase in the stress anisotropy. This major change begins at about 400°C. The rapid reduction in L_p, however, ceases at about 750°C. Upon relatively slow cooling of the fibre, the beat length returns to an altogether and always smaller value, whose exact magnitude depends on the temperature treatment the fibre has received. A second heating and slow cooling of the fibre results in only a small degree of hysteresis as indicated by curve (*b*). If the fibre is now heated and cooled rapidly by switching off the furnace, the *reverse* hysteresis is observed, producing a beat length longer than the end point of curve (*b*), although it still is approximately 40% smaller than the as-received value. Similar hysteresis phenomena are observed in the axial stress in the preform and also other fibre structures, i.e. elliptical cores and claddings which utilise boron-doped silica to produce anisotropic stress.*

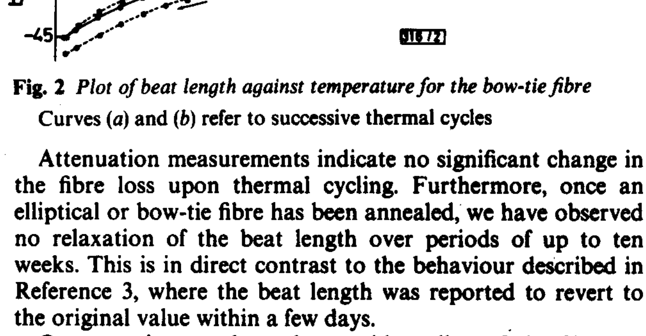

Fig. 2 *Plot of beat length against temperature for the bow-tie fibre*

Curves (*a*) and (*b*) refer to successive thermal cycles

Attenuation measurements indicate no significant change in the fibre loss upon thermal cycling. Furthermore, once an elliptical or bow-tie fibre has been annealed, we have observed no relaxation of the beat length over periods of up to ten weeks. This is in direct contrast to the behaviour described in Reference 3, where the beat length was reported to revert to the original value within a few days.

Our experiments show that rapid cooling of the fibre (or preform) is responsible for the thermal hysteresis of the beat length. It would appear that quenching the fibre during the draw prevents the development of the full anisotropic stress potentially available in the stress-producing sections of the structure. Consequently the possibility exists for significantly enhancing the birefringence by 'on-line' annealing of the fibre.

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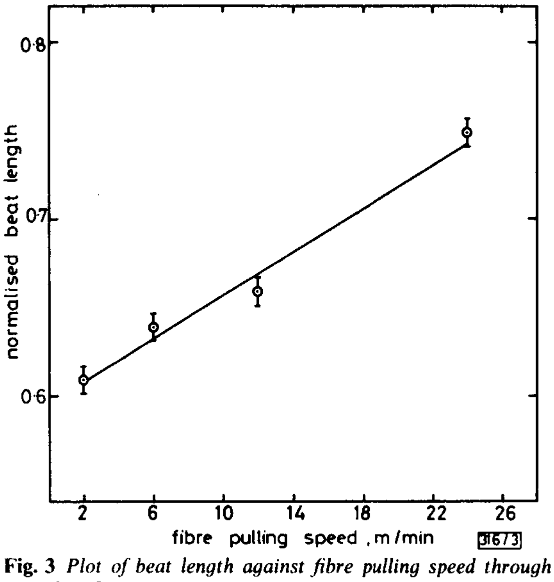

Fig. 3 *Plot of beat length against fibre pulling speed through 'on-line' annealing furnace*

Beat length is normalised to the unannealed value

Fig. 3 shows a plot of the beat length against fibre pulling speed when the fibre is annealed 'on-line' by passing through a four-zone annealing furnace prior to being wound on the drum, as described above. Even at relatively fast pulling speeds (and hence cooling rates), significant reductions in the beat length are observed compared to the 'unannealed' value. This is consistent with our earlier annealing experiments, where it was found that fairly rapid cooling rates still produce substantial improvements in birefringence. Again we have observed no relaxation of beat length to the original 'as-received' value over periods of many days.

* Ourmazd, A., Varnham, M. P., Burch, R. D., and Payne, D. N. 'Thermal properties of highly birefringent optical fibres and preforms' (to be published)

Conclusions: Quenching has been established as being responsible for the thermal hysteresis behaviour of highly birefringent fibres utilising borosilicate glass for stress production. Annealing of lengths of test fibre, as well as 'on-line' annealing of the fibre during the drawing process, have been shown to produce substantial increases in the already high values of birefringence achieved. 'On-line' annealing of highly birefringent fibres therefore appears to be an essential process for utilising levels of stress potentially available in structures with borosilicate stress-producing sections.

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