OPTICAL FIBRE SENSOR

EFFECTS OF TEMPERATURE ON THE BIREFRINGENCE PROPERTIES OF POLARISATION MAINTAINING FIBRES

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INTRODUCTION

Many optical fibre sensors such as interferometers and gyros require the transmission of stable colinear polarised light. External perturbations such as bends and twists, however, lead to variations in the output polarisation state of light guided by ordinary single-mode optical fibres (Payne et al (1)). Highly birefringent fibres attempt to overcome this difficulty by deliberately introducing levels of intrinsic birefringence $\Delta\beta$ in excess of that produced by external factors, thereby rendering the polarisation state immune to all but the most major perturbations. Such fibres are characterised by their modal birefringence B, defined as $n_x - n_y = \lambda/2\pi\ \Delta\beta$, where n_x and n_y refer to the refractive indices for light polarised along the fibre principle axes x and y respectively. A commonly quoted figure of merit, however, is the so-called beat length $L_p = \lambda/B$ at a given wavelength.

High values of birefringence, (small beat lengths) can be obtained by using the anisotropic thermal-stress produced by the incorporation of doped regions having expansion coefficients different from that of silica within the fibre. A variety of such structures have been reported in the literature (Birch et al (2), Kaminow et al (3), Hosaka et al (4), Katsuyama et al (5)). They can be classified into two cagetories; those with elliptical claddings and those which utilise "side-pit" structures. The highest values of birefringence (smallest values of beat length) reported to date have been achieved in our laboratory by means of the so-called "bow-tie" side-pit structure; beat lengths of 0.55mm at a wavelength of 633nm have been successfully produced. Such high values of birefringence have also recently been used to produce fibres which transmit a single polarisation state only (Varnham et al (6), Birch et al (7)).

High birefringence fibres, which rely on the expansion mismatch between the differently-doped parts of their structure for the introduction of high values of internal stress, are not easily susceptible to full stress analysis because the thermoviscoelastic properties of the doped glasses are not well-known. Moreover, since fibre sensors are likely to operate in hazardous environments, they may be subjected to elevated temperatures. For all these reasons it is important to investigate the behaviour of highly-birefringent fibres as a function of temperature. Such a study would yield data on the aging properties of these fibres, shed light on the importance of different parameters in determining the birefringence and thus help in the design and development of high-birefringence and polarising fibres.

The temperature-dependent behaviour of a number of elliptically-clad fibres was reported by Ramaswamy et al (8), where a hysteresis effect in the beat length was found upon temperature cycling of the fibres. The fibres studied, however, did not exhibit the very high values of birefringence now available and furthermore, no firm conclusions were reached on the origin of the hysteresis effect.

In this paper we report the results of an investigation designed to establish the temperature-dependent behaviour of highly birefringent fibres of different structure and composition. We elucidate the origin of the hysteresis effect and discuss the implications of our results so far as the use of highly birefringent and polarising fibres in sensors are concerned.

EXPERIMENTAL

In order to determine the thermal behaviour of the fibre birefringence, linearly-polarised light (λ = 633nm) was launched into the test fibre at 45° to the principle axes, with most of the fibre enclosed in a furnace consisting of a small silica tube and resistance wire wrapping. A photo-elastic modulator was used to yield sin Δ and cos Δ of the output light, where Δ is the retardance (see for example Barlow and Payne (9)). The change 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.

Figures 1(a) and (b) show the structure of a bow-tie fibre manufactured in our laboratory; the stress-producing side-pit sections which are doped are clearly visible.

RESULTS

Bow-Tie Structure with Borosilicate Stress-Producing Sections

Figure 2 is a plot of the relative change in the beat length L_p as a function of temperature for this bow-tie fibre, which had an initial beat length of 1.1mm. Curve (a) shows the behaviour of the "as-received" fibre upon heating. Initially the beat length increases with temperature. This is due to the reduction in the stress anisotropy at the core because of the differential expansion of the borosilicate sections tending to relieve the thermal stress. Subsequently, however, the beat length undergoes a dramatic reduction indicating an increase in the stress anisotropy at the core. This major change begins at about 400°C, although it has occasionally been observed to commence at temperatures as low as 350°C. Indeed, the substantial reduction in L_p takes place even if the fibre temperature is held constant at 400°C or above. The rapid reduction in L_p ceases at about 750°C. Upon relatively slow-cooling of the fibre, the beat length returns to an altogether different 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) of Figure 2.

If the fibre is now heated and quenched by switching off the furnace (Figure 3, curve (c)) the reverse hysteresis is observed, producing a beat length longer than the end point of curve (b), although it is still approximately 40% smaller than the as-received value. Subsequent heating and slow-cooling (Figure 3, curve (d)) shows the return of the hysteresis observed in curve (a). Similar hysteresis phenomena are observed not only in the axial stress in the preform, but also in other fibre structures, i.e. elliptical claddings, which utilise boron-doped silica to produce anisotropic stress (Ourmazd et al (10)).

Attenuation measurements indicate no significant change in the fibre loss upon thermal cycling. Furthermore, once a fibre has been annealed, we have observed no relaxation of the beat length over periods of up to ten weeks.

Bow-Tie Structure with Fluorophosphosilicate Stress-Producing Sections

Figure 4 is again a plot of the relative change in beat length upon thermal cycling of such a fibre. Curve (a), which represents the first cycle, indicates an initial reduction in the beat length with temperature, implying increasing stress anisotropy at the core. This should be contrasted with curve (a) of Figure 2 for the borosilicate bow-tie, where the initial temperature rise increases the beat length, thus implying a reduction in the stress anisotropy. The reduction in the beat length of the fluorophososposilicate, however, is arrested at about 250°C, when the beat length increases dramatically. In short, curve (a) of Figure 4 indicates that this fibre is exhibiting the reverse of the hysteresis observed for the borosilicate bow-tie. Curve (b) represents the second heating and slow-cooling cycle, while curve (c) of Figure 5 shows that fast-quenching of the fluorophosphosilicate fibre reduces the beat length. The final heating and slow-cooling cycle of curve (d) establishes quenching as again being responsible for the thermal hysteresis behaviour.

DISCUSSION

The results presented above establish quenching as being responsible for the thermal hysteresis of the birefringence in structures utilising thermal stress, irrespective of the particular structure and composition of the stress-producing parts. Indeed the thermal hysteresis behaviours described above have been related to the volume changes that take place in the stress-producing sections upon annealing (10).

In the borosilicate bow-tie, the core is under tension as a consequence of the differential contraction of the borosilicate stress-producing sections. The initial increase in temperature brings about a reduction in the differential contraction and hence the stress anisotropy at the core, thereby increasing the beat length. Annealing of the fibre at temperatures in excess of 400°C brings about a volume compaction of the borosilicate sections (Tool (11)), producing a larger stress anisotropy and reducing the beat length.

In the fluorophosphosilicate bow-tie, however, the core is in compression (Ourmazd et. al (12)). The initial temperature rise, therefore, by increasing the volume of the fluorophosphosilicate parts, increases the stress anisotropy thus reducing the beat length. Subsequent annealing at temperatures higher than 250°C again brings about a reduction in the volume of the fluorophosphosilicate stress-producing parts, thereby reducing the stress anisotropy and increasing the beat length (12).

The importance of understanding the thermal properties of high-birefringence and polarising structures so far as the use of such fibres for sensor applications is concerned is now apparent. In applications where the change of birefringence is utilised to measure external parameters such as temperature, fibres incorporating stress-producing borosilicate sections must not be used at temperatures higher than 300°C to avoid hysteresis effects. In the case of fibres with flurophosphosilicate parts, the range of operation must not exceed 100°C.

However, the large majority of sensors simply require values of intrinsic fibre birefringence in excess of those likely to be produced by external perturbations. In such cases it is pointed out that bow-tie fibres incorporating borosilicate parts exhibit high values of birefringence up to temperatures in excess of 750°C. Thus the fibre of Figures 2 and 3 is characterised by a beat length shorter than 2mm throughout the temperature range of examination. Furthermore, such fibres show no deterioration of their birefringence properties upon thermal cycling and should therefore be immune to aging problems. Borosilicate bow-tie fibres can therefore be recommended for use in sensors likely to operate in hazardous environments at elevated temperatures of up to 750°C.

Bow-tie fibres incorporating flurophosphosilicate parts, however, suffer from significant reductions in their birefringence at high temperatures and cannot be recommended for operation at temperatures much in excess of 300°C. Elliptically-clad fibres with borosilicate parts also exhibit appreciable reductions in birefringence at temperatures in excess of 600°C (see ref. (10)). Their use at elevated temperatures must therefore be adopted with caution.

CONCLUSIONS

The results described in this paper highlight the importance of the thermal history of fibres incorporating stress-producing parts in determining their birefringence properties. Since bow-tie fibres with borosilicate parts exhibit high values of birefringence up to temperatures in excess of 750°C, they are suitable for use in fibre sensors, which do not rely upon changes in the fibre birefringence for the measurement of external parameters. For the latter applications the range of operation must not exceed 300°C.

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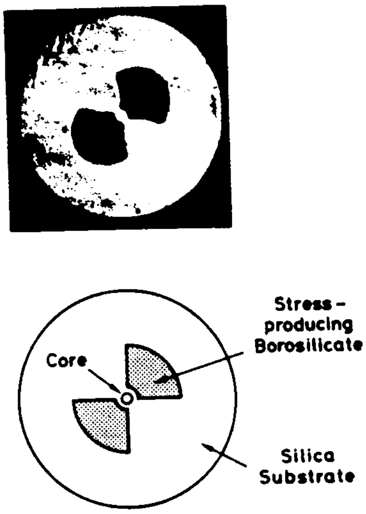

Figure 1 Optical micrograph and schematic diagram of a bow-tie fibre. In this case the side pits are boron doped.

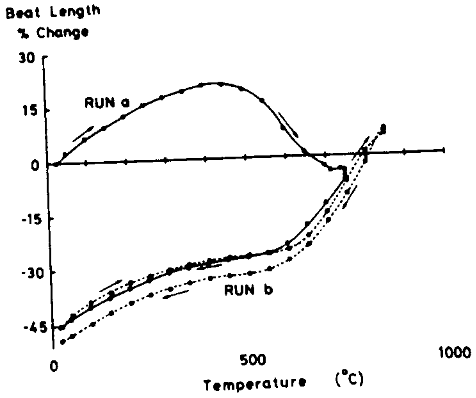

Figure 2 A plot of relative change in beat length as a function of temperature for a borosilicate bow-tie fibre. Runs (a) and (b) refer to successive thermal cycles, the fibre having been cooled slowly on each occasion. The as-received fibre is in a highly quenched state and run (a) refers to the annealing of such a fibre.

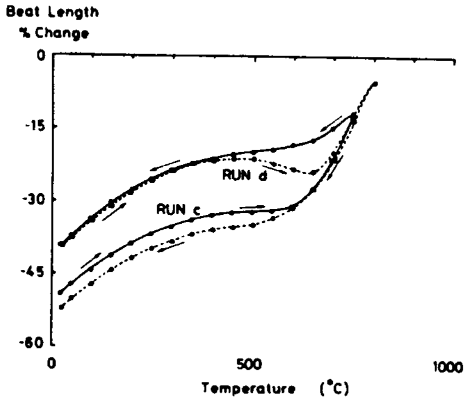

Figure 3 A plot of relative change in beat length as a function of temperature for the borosilicate fibre of Figure 2. Runs (c) and (d) succeed (a) and (b) of Figure 2. The fibre is quenched in run (c) by switching off the furnace.

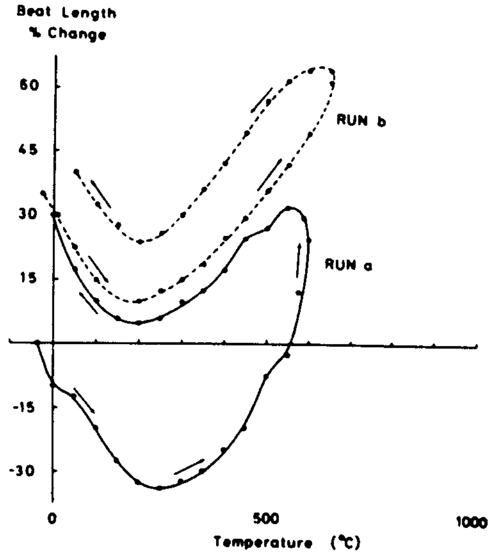

Figure 4 A plot of relative change in beat length as a function of temperature for a fluorophosphosilicate bow-tie fibre. Runs (a) and (b) refer to successive thermal cycles, run (a) showing the annealing behaviour of the as-received (highly quenched) fibre. Note the hysteresis is the reverse of that observed for borosilicate fibre.

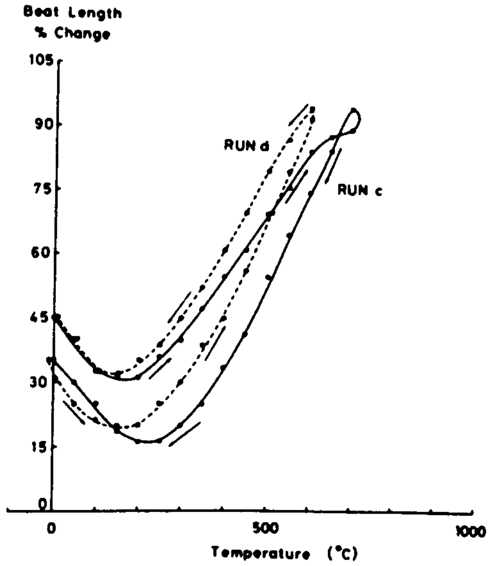

Figure 5 A plot of relative change in beat length as a function of temperature for the fluorophosphosilicate fibre of Figure 4. Runs (c) and (d) succeed (a) and (b) of Figure 4. The fibre is quenched in run (c) by switching off the furnace.