Reprinted from **Applied Optics,** Vol. 22, page 2374, August 1, 1983

Thermal properties of highly birefringent optical fibers and preforms

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Temperature cycling of highly birefringent optical fibers and preforms has been used to investigate the thermal properties of bow-tie and elliptically clad structures. The thermal hysteresis of the birefringence is shown to be a direct consequence of the thermal history of the fiber or preform and has been related to volume changes in the stress-producing borosilicate sections. Annealing increases the axial stress as well as the stress anisotropy and hence the birefringence. Increases of up to a factor of 2 in the birefringence on suitable thermal treatment indicate a new method for further improvement of high birefringence fibers. The implications of the results in the design, fabrication, and use of such fibers are discussed.

I. Introduction

It is well known that external perturbations, such as bends, twists, and side pressure, lead to variations in the output polarization of light guided by ordinary single-mode optical fibers.[1] Such variations are usually random and unpredictable, thus making normal fibers unsuitable for applications that require a stable polarization state to be transmitted.

Highly birefringent fibers, however, attempt to overcome this difficulty by deliberately introducing levels of intrinsic birefringence in excess of that produced by external factors, thereby rendering the polarization state relatively immune to all but the most major perturbations. Such fibers are characterized by their 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 polarized along the fiber principal 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.

Very high values of birefringence (see, e.g., Ref. 2) can be obtained by using the anisotropic thermal stress produced by high-expansion doped regions incorporated within the fiber. A variety of such structures have been reported in the literature.[3-5] They can be classified into two categories; those with elliptical core and/or cladding and those which utilize 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; best lengths of 0.55 mm at a wavelength of 633 nm have been successfully produced.

Most highly birefringent fibers, which rely on the expansion mismatch between the differently doped parts of their structure for the introduction of high values of internal stress, possess complex structures. They are therefore not easily susceptible to full stress analysis. Furthermore, the thermal properties of the doped glasses are not well known. For both these reasons it is important to investigate the behavior of highly birefringent fibers as a function of temperature. Such a study would be expected to yield data on the aging properties of these fibers and shed light on the importance of different parameters in determining the birefringence.

The temperature-dependent behavior of a number of elliptically clad fibers was reported in Ref. 6, where a hysteresis effect in the beat length was found upon temperature cycling of the fibers. The fibers 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.

{Since the submission of this manuscript for publication, a further work on the temperature dependence of birefringence has been reported by S. C. Rashleigh and M. J. Marrone [Opt. Lett. 8, 127 (1983)]. These authors annealed an elliptically clad fiber with borophosphosilicate stress-producing parts to temperatures in excess of 1200°C, when devitrification occurred. They state that: "Detailed measurements on the reversibility of (the) temperature dependence have not been performed," and that: "The origin of the non-

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Received 19 January 1983.
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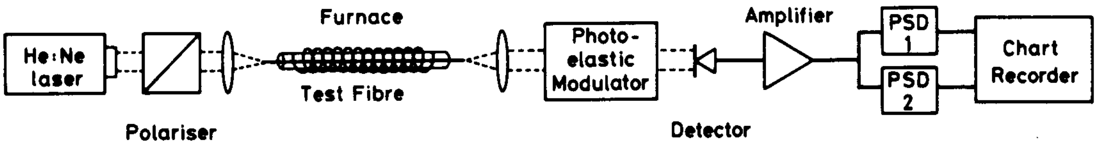


Fig. 1. Experimental arrangement used to monitor the retardance of test fibers as a function of temperature.

linear behavior of the fiber's birefringence is unclear at this stage."}

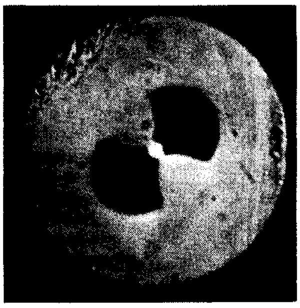
In this paper we report the results of an investigation designed to establish the temperature-dependent behavior of two types of highly birefringent fiber, namely, side-pit and elliptically clad structures, which exhibit extreme values of birefringence. We propose an explanation for the hysteresis effect, compare and contrast side-pit and elliptically clad structures, and discuss the implications of our results so far as the design, fabrication, and use of highly birefringent fibers are concerned.

II. Experimental

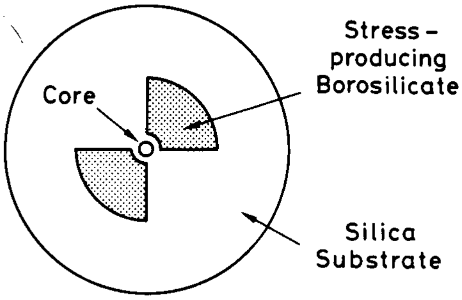
All the measurements reported in this paper were made at a wavelength of 633 nm using a He–Ne laser. Linearly polarized light was launched into 40 cm of the test fiber at 45° to the principal axes. Most of the fiber length was enclosed in a 30-cm long furnace consisting of a silica tube and resistance wire wrapping (Fig. 1). A photoelastic modulator was used to yield $\sin\Delta$ and $\cos\Delta$ of the output light, where Δ is the retardance. The change in Δ, uniquely determined by the combination of $\sin\Delta$ and $\cos\Delta$, was recorded as a function of temperature and time in order to monitor the fiber birefringence, or equivalently, beat length. The use of the photoelastic modulator provides an exceedingly sensitive and fast means of monitoring the fiber birefringence.[7] Absolute measurements of the beat lengths were also performed before and after heat treatment.

Experiments were also carried out to observe changes in the axial stress as a function of temperature in the preform. For such measurements, the retardance produced by the preform under transverse illumination (which uniquely determines the axial stress[8]) was monitored by means of the photoelastic modulator. The preform was heated directly by wrapping resistance wire around it.

Figures 2(a) and (b) show the structure of the bow-tie fiber[2] studied. The boron-doped sectors producing the stress are clearly visible. The fiber was fabricated in our laboratory and exhibited a beat length of 1.1 mm before any thermal cycling. A typical boron concentration in our fibers is 20 mol % in the gas phase. The fiber was pulled at a speed of 0.5 m/sec with a drawing tension of 50 g. Figures 3(a) and (b) illustrate the structure of the elliptically clad fiber investigated. The fiber, manufactured by Hitachi Cable, Ltd., had a beat length of 3.4 mm before thermal treatment. Unfortunately neither the dopants nor their concentrations were known, although the stress-producing parts were clearly doped with boron and index-matched with Ge or P. Both fibers were heated without any protective coating.

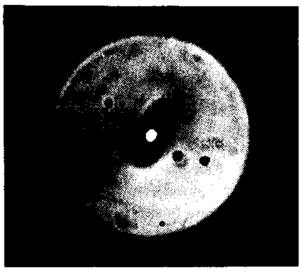


(a)

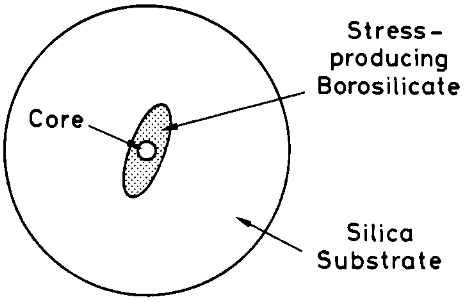


(b)

Fig. 2. Micrograph (a) and sketch (b) of the cross-sectional structure of the bow-tie fiber.



(a)



(b)

Fig. 3. Micrograph (a) and sketch (b) of the cross-sectional structure of the elliptically clad fiber.

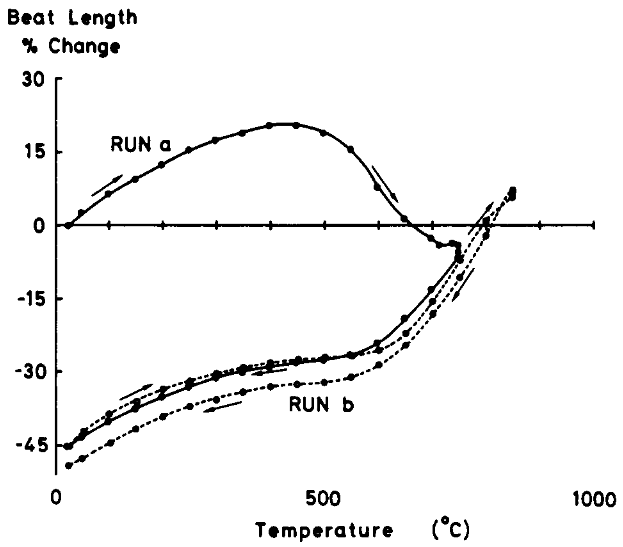


Fig. 4. Plot of beat length vs temperature for the bow-tie fiber. Curves *a* and *b* refer to successive thermal cycles.

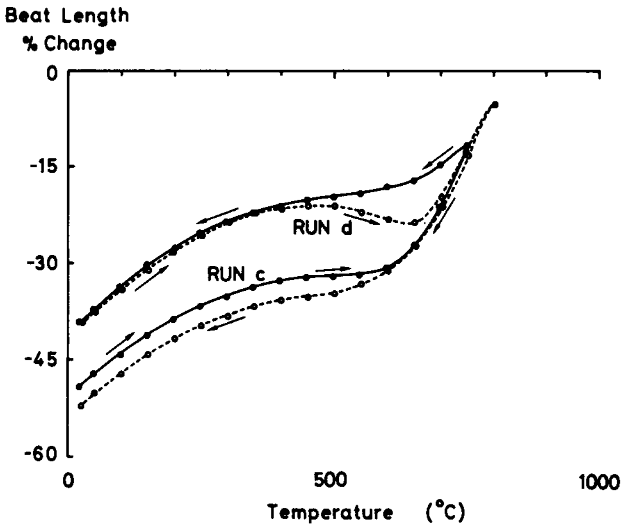


Fig. 5. Plot of beat length vs temperature for the bow-tie fiber. Runs *c* and *d* succeed *a* and *b* of Fig. 4. Curve *c* is produced by rapid cooling of the fiber.

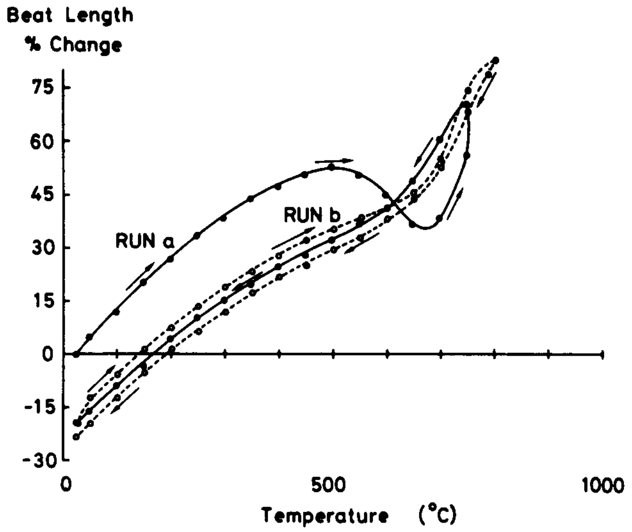


Fig. 6. Plot of beat length vs temperature for the elliptically clad fiber. Curves *a* and *b* refer to successive thermal cycles.

III. Results

A. Bow-Tie Structure

Figure 4 is a plot of the relative change in the beat length L_p as a function of temperature for the bow-tie fiber. Curve *a* shows the behavior of the as-received fiber on heating at a rate of 30°/min. 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 ~400°C, although it has been sometimes observed to commence at temperatures as low as 350°C. Indeed, the substantial reduction in L_p takes place even if the fiber temperature is held constant at 400°C or over. The rapid reduction in L_p, however, ceases at ~750°C. Upon relatively slow cooling (~30°/min) of the fiber, the beat length returns to an altogether different and always smaller value, whose exact magnitude depends on the temperature treatment the fiber has received. A second heating and slow cooling of the fiber results in only a small degree of hysteresis as indicated by curve *b*.

If the fiber is now heated and quenched by switching off the furnace, which corresponds to a cooling rate of ~150°/min, (Fig. 5, curve *c*), the beat length returns to a larger value than the starting point of curve *c*, the fiber thus exhibiting a reverse hysteresis. Subsequent heating and slow cooling (Fig. 5, curve *d*) shows the return of the hysteresis observed in curve *a*.

The same hysteresis phenomena are observed in the axial stress in the preform. A first heating and slow cooling of the as-received preform results in a value of axial stress after the cycle, which is higher than the starting value, indicating a larger value of birefringence. The axial stress can again be manipulated by suitable heating and cooling procedures to be higher or lower than the starting point, in exactly the same manner as for the fiber.

Once a fiber has been heated and cooled slowly, we have observed no relaxation of the beat length to the original as-received value over periods of up to ten weeks. This is in direct contrast to the behavior reported in Ref. 5, where the beat length was observed to revert to the original value over a period of a few days. Attenuation measurements indicate no significant change in the fiber loss on thermal cycling.

B. Elliptically Clad Fiber

Figure 6 shows the thermal cycling behavior of an elliptically clad fiber. Curve *a* represents the first heating and slow cooling cycle of the as-received fiber. Again the initial increase in L_p is followed by a rapid reduction beyond ~500°C, which is followed by a further fast increase as the temperature exceeds 650°C. Slow cooling results in significant hysteresis, with the beat length returning to a value substantially less than the starting point. The second heating and slow cooling cycle (Fig. 6, curve *b*) produces little hysteresis, a behavior similar to that observed previously in curve *b* of Fig. 4 for the bow-tie fiber.

Figure 7, curve *c* illustrates the effect of subsequent heating and quenching of the fiber. Again a reverse hysteresis occurs, resulting in a beat length larger than the starting value. Further heating and slow cooling of the fiber (curve *d*) reintroduces a hysteresis curve and again reduces the beat length. We have observed no relaxation of the beat length of a slowly cooled elliptically clad fiber to its original as-received value for periods of observation up to ten weeks.

IV. Discussion

The results of the thermal cycling and quenching experiments described in the previous section provide strong evidence that rapid quenching of the fiber (or indeed the preform) is responsible for the thermal hysteresis behavior of the birefringence. The as-received fiber, pulled at high speed from the hot preform, is in a highly quenched state and therefore exhibits the largest degree of hysteresis. The degree of hysteresis can be manipulated by suitable thermal cycling of the fiber or preform; rapid cooling reduces the final birefringence and axial stress, while slow cooling increases both. The hysteresis, although of differing magnitude, is observed in both the bow-tie and elliptically clad structures and must therefore be independent of the particular structure investigated.

The surprising point is the increase in the birefringence and axial stress on annealing of the fiber or the preform. However, quenched borosilicate glass is known to undergo various structural changes at ~400°C, with no significant change in viscosity.[9] Figure 8 represents the classic expansion results of Tool[10] on various borosilicate glass containing a variety of secondary dopants. Upper curve *1* represents the normalized length change $(\Delta l)/l$ of a rapidly cooled sample on heating, while curve *2* shows the behavior of a stabilized and slowly cooled sample. The similarity between Fig. 8 curves *1* and *2* and Fig. 6 curves *a* and *b* is remarkable and leads us to offer the following explanation for the observed fiber behavior.

Since there is no abrupt change in viscosity, the rapid changes at 400°C must be viewed as taking place essentially in the solid state. Thus the increase in the birefringence between 400 and 700°C is due to volume reduction in the borosilicate sections of the fibers, with virtually no accompanying viscous flow. The compaction of the borosilicate glass in the stress-producing region of the quenched fiber increases the stress and hence the birefringence. No stress relaxation can take place because no appreciable viscous flow is possible. On the other hand, as indicated by the convergence of curves *1* and *2* of Fig. 8, viscous flow is able to take place at or near 700°C, giving rise to some stress relief in the fiber and an arrest of the rapid increase in the birefringence.

Slow cooling of the fiber or preform enables the borosilicate glass to return to room temperature essentially

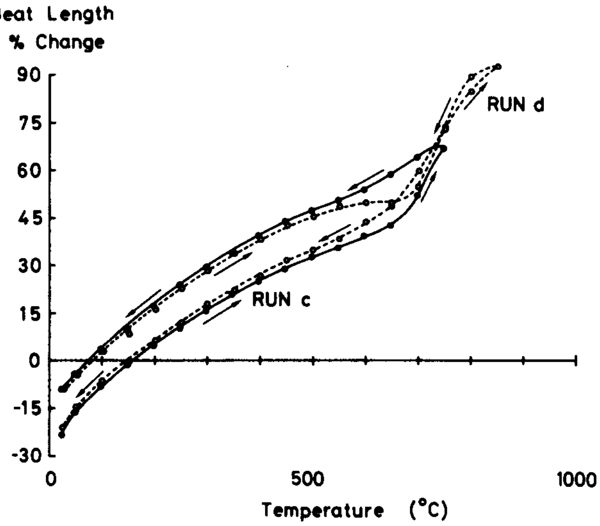


Fig. 7. Plot of beat length vs temperature for the elliptically clad fiber. Runs *c* and *d* succeed *a* and *b* in Fig. 6. Curve *c* is produced by rapid cooling of the fiber.

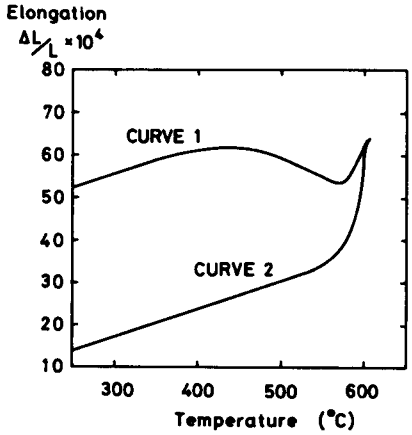


Fig. 8. Plot of normalized length change $(\Delta l)/l$ vs temperature for borosilicate glass (after Tool[10] reproduced with kind permission from J. Am. Ceram. Soc.).

via a path similar to Fig. 8, curve *2*, although an exact following of this curve would require exceedingly slow cooling. The final value of stress at room temperature is thus increased substantially because the stress-producing regions of the fiber structure have reduced in volume significantly compared with that in the quenched state.

It is known[11] that volume changes in glasses are accompanied by changes in the refractive index. A change in the refractive index of the stress-producing section, however, would not be expected to give rise to changes in birefringence since these parts carry little or no optical power. Furthermore, although the borosilicate component undergoes substantial changes at ~400°C, the germania-doped core would not be expected to exhibit significant and large volume changes at such low temperatures. We therefore deduce that the changes in the birefringence come about as a consequence of a stress increase in the core brought about by volume compaction in the stress-producing borosilicate sections of the fiber during thermal cycling.

It can be shown that a plot of L_p vs T would be expected to follow closely the shape of the $(\Delta l)/l$ vs T curves of Fig. 8 as follows. The birefringence B is essentially determined by the difference in the final dimensions of the stress-producing sections compared with the rest of the structure. Let us take for simplicity the elliptically clad structure of Fig. 3. At the fictive temperature of the cladding, the borosilicate glass region is substantially liquid and cannot support anisotropic stress. The core is totally surrounded by the liquid cladding and therefore experiences only hydrostatic forces, regardless of whether the core itself is solid or liquid. Hence no stress birefringence can be present.

Let V_f be the volume of the borosilicate cladding at the fictive temperature. Then as the temperature is reduced, the birefringence is given by

$$B = A[V_f - V(T)], \tag{1}$$

where $V(T)$ is the volume of the stress-producing cladding at temperature T and A is a constant, which depends on the glass optical and mechanical properties.

$$V(T) = \int V_r \cdot \alpha_v dT, \tag{2}$$

where V_r is the volume at room temperature and α_v is the volume expansion coefficient. Thus

$$B = AV_f\left(1 - \frac{V_r}{V_f}\int \alpha_v dT\right) \cdot \tag{3}$$

Or since $\alpha_v = 3\alpha_l$ where α_l is the linear expansion coefficient $[d/(dT)][(\Delta l)/l]$

$$B = AV_f\left(1 - \frac{3V_r}{V_f}\int \alpha_l dT\right) \cdot \tag{4}$$

The beat length L_p is given by

$$L_p = \frac{\lambda}{B} = \frac{\lambda}{AV_f\left(1 - \frac{3V_r}{V_f}\int \alpha_l dT\right)}, \tag{5}$$

or

$$L_p \simeq \frac{\lambda}{AV_f}\left(1 + \frac{3V_r}{V_f}\int \alpha_l dT\right) \cdot \tag{6}$$

Thus substituting for $\alpha_l = [d/(dT)][(\Delta l)/l]$

$$L_p \simeq E\left(1 + F\frac{\Delta l}{l}\right), \tag{7}$$

where E and F are constants. Equation (7) shows that the shape of a plot of L_p vs T should be essentially the same as that of the temperature variation of the dimensions of the stress-producing parts of the fiber as confirmed experimentally (compare the similarity between Figs. 3 and 5 and Fig. 8).

One major difference, however, exists between the two structures investigated, namely, the bow-tie and the elliptical cladding structures. The difference is illustrated in Fig. 9 where the upper and lower curves are plots of the absolute birefringence for the bow-tie and elliptical cladding fibers, respectively. The curves are plotted for temperatures up to 350°C before any structural compaction takes place. From the similarity between the slopes of the two curves it can be inferred that the expansion coefficient and hence the dopant concentration must be similar in the stress-producing regions of the two different structures. However, the birefringence of the bow-tie fiber is higher by a factor of 3 owing to its greater stress-birefringence efficiency.[2] Furthermore, using a computer fit to the linear section of the data the birefringence of the elliptically clad fiber can be extrapolated to zero at ~900°C (which corresponds well to the temperature when the cladding is liquid and can support no stress anisotropy). On the other hand the birefringence of the bow-tie fiber does not become zero until ~1800°C, i.e., far beyond the temperature when the stress-producing parts are liquid. This highlights a major difference between the two structures, namely, that unlike the elliptically clad fiber, the bow-tie fiber exhibits high birefringence even when the stress-producing parts can support only hydrostatic (isotropic) stress. Thus the extrapolated upper curve of Fig. 9 can be divided into two parts; one where hydrostatic stress in the bow-tie sectors is giving rise to birefringence (viscoelastic birefringence) and the other where the sectors are solid and thus stress anisotropy is present. If the two components of birefringence are denoted by B_v and B_a, respectively, Fig. 9 illustrates two points of major importance. First, that the viscoelastic component of the stress B_v is significant in determining the birefringence in side-pit structures, and second, that the viscoelastic and anisotropic contributions B_v and B_a add constructively to produce a large value of birefringence. This factor, together with the higher values of B_a produced by side-pit structures,[2] emphasizes the superiority of such fibers to the elliptically clad structure.

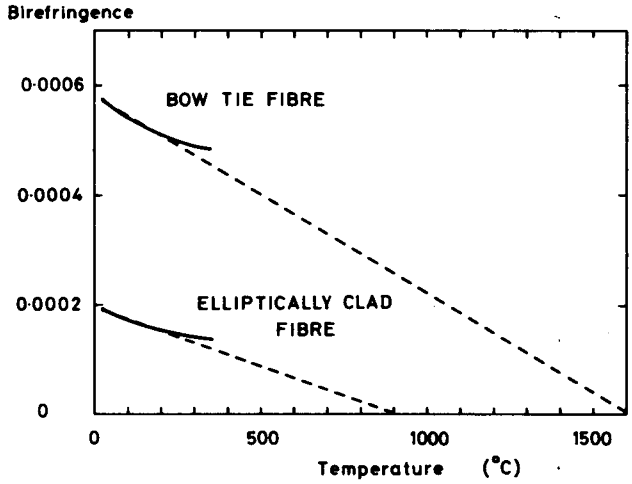


Fig. 9. Plots of birefringence vs temperature for the bow-tie and elliptically clad fibers.

A further important implication of the results presented in Sec. III is that the fast pulling and hence rapid quenching of the fiber from the preform prevents the development of the full stress potentially available. It is therefore possible to obtain substantial increases (up to a factor of 2) in birefringence by suitable pulling and/or annealing procedures.

Since the submission of this manuscript, we have demonstrated that suitable on-line annealing of the drawing process can produce a 70% increase in the birefringence. This aspect of the work was briefly reported in a short note [Electron. Lett. **19**, 143 (1983)].

V. Conclusions

We have established that quenching is responsible for the hysteresis observed in the thermal cycling of the birefringence in highly birefringent optical fibers. Furthermore we deduce that volume changes in the stress-producing borosilicate regions of these fibers are directly responsible for the birefringence hysteresis.

Our experiments have elucidated the contribution to the birefringence of the viscoelastic component of stress in side-pit structures indicating this contribution to be substantial and in the same direction as that produced by the normal anisotropic contribution.

This study has also provided indications with regard to possible ways of significantly improving the already high values of birefringence obtainable in fibers. We also conclude that, due to their hysteresis properties, highly birefringent fibers may not be suitable for use as temperature sensors at high temperatures.

The authors express their gratitude to A. J. Barlow and R. J. Mears of this laboratory for their kind assistance and interest. They are also grateful to H. Matsumura of Hitachi Cable, Ltd. for the provision of the elliptically clad fiber. A Research Fellowship was provided by the Pirelli General Cable Co. (DNP) and a Research Studentship by British Aerospace plc (MPV).

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