POLARIMETRIC STRAIN GAUGES USING HIGH BIREFRINGENCE FIBRE

Indexing terms: Optical fibres, Birefringence

When a highly-birefringent fibre is stretched, the birefringence changes. The phenomenon is shown to result from a difference in Poisson's ratio of the two glasses from which the fibre is constructed. Experimental verification is given and a simple polarimetric strain gauge made from bow-tie fibre is demonstrated.

Introduction: Polarimetric sensors utilise the relative change in optical path length which occurs between the two orthogonally polarised modes of a fibre when it is subjected to transverse stress. The technique is attractive, as polarimetric sensors are considerably simpler to construct than their better-known interferometric-sensor counterparts and can have similar sensitivity. Recently it has been reported[1] that stretching a highly-birefringent fibre can similarly affect the differential optical phase (i.e. the birefringence), a somewhat surprising result. The phenomenon can be used as the basis for a variety of simple polarimetric sensors,[1] e.g. a strain gauge.

The purpose of this letter is to elucidate theoretically the mechanism whereby stretching the fibre changes its birefringence. We employ a simple analytic expression previously developed[2] for the birefringence produced by thermal stress in the fibre. The theory is then verified experimentally. Finally we demonstrate how a simple, all fibre, polarimetric sensor can be constructed using highly-birefringent bow-tie fibres[3] as both sensor fibre and as a polariser.[4] The experiment also shows the ease with which these highly asymmetric fibres can be jointed with UV-curable adhesives.[5]

Theory: The modal birefringence B is related to the expansion-coefficient profile $\alpha(r, \theta)$ of a fibre having one axis of mirror symmetry (see inset of Fig. 1) and a normalised outer radius $r = 1$, by:[2]

$$B = \frac{CET}{1-\nu}\int_0^1 \frac{1}{\pi}\int_0^{2\pi} \alpha(r, \theta) \times \cos 2\theta \, d\theta (r^{-1} - 3r^3)\, dr \qquad (1)$$

where C is the stress optic coefficient, T is the difference between ambient temperature and the lowest fictive temperature of the glasses within the fibre, E is Young's modulus and ν is Poisson's ratio.

The derivation of eqn. 1 assumes that E and ν are uniform across the fibre cross-section.[2] If this were the case, then by Saint Venant's principle,[6] no variation in transverse stresses, and hence B, would occur on stretching the fibre. On the other hand, if ν does vary, then stretching the fibre in the z-direction with a uniform strain ε_z would result in free strains in the transverse x- and y-directions $\varepsilon_x = \varepsilon_y = -\nu\varepsilon_z$, which are analogous to the free thermal strains $\varepsilon_x = \varepsilon_y = \varepsilon_z = \alpha T$ occurring as the fibre cools.[6] Hence, if the variation of E and ν across the fibre cross-section is small, then eqn. 1 can be modified to give:

$$B_{st} = -\frac{CE\varepsilon_z}{1-\nu_0}\int_0^1 \frac{1}{\pi}\int_0^{2\pi} \nu(r, \theta) \times \cos 2\theta \, d\theta (r^{-1} - 3r^3)\, dr \qquad (2)$$

where B_{st} is the modal birefringence induced by stretching, and ν_0 is the value of ν seen at the core.

We now assume that $\alpha(r, \theta)$ is proportional to $\nu(r, \theta)$, a not unreasonable assumption, as both are related to the dopant concentration. This leads to the following formula, which relates the extension Δl required to induce a 2π phase change in the retardance of any length of high birefringence fibre to its beat length $L_p = \lambda/B$:

$$\Delta l \simeq -\frac{(\alpha_2 - \alpha_1)T}{\nu_2 - \nu_1} L_p \qquad (3)$$

where λ is the wavelength, and α_1, ν_1 and α_2, ν_2 are the expansion coefficients and Poisson's ratios in the different regions 1 and 2, respectively (see inset of Fig. 1).

The application of eqn. 3 is illustrated in Fig. 1 where the extension Δl is plotted against the beatlength L_p for the silica/borosilicate bow-tie fibre shown in the inset. We have taken $\nu_2 - \nu_1 = 0{\cdot}02$, which is the approximate difference between Poisson's ratio for borosilicate glasses and silica,[7] and $(\alpha_2 - \alpha_1)T = -10^{-3}$, a fairly typical value for bow-tie fibres.[2] Thus, from Fig. 1, we would expect a 50 μm extension to produce a 2π change in the retardance of a 1 mm beat-length fibre, regardless of the fibre length, cross-sectional geometry and the dopant concentrations of the stress-applying sections.

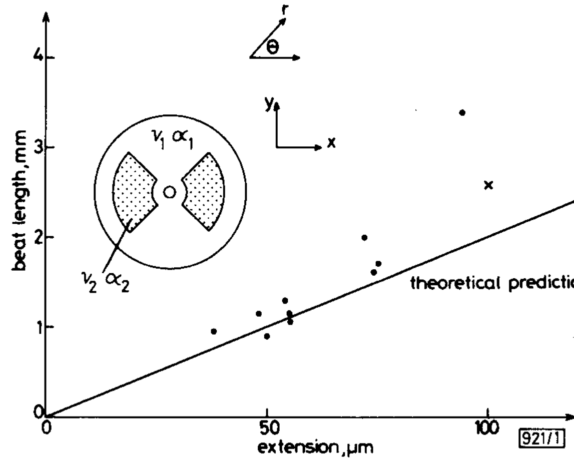

Fig. 1 *Calculated extension required to induce 2π phase change in retardance for bow-tie fibres against beat length*

Also shown are experimental results measured in bow-tie fibres (dots) and Rashleigh's result[1] measured in an elliptical jacket fibre (cross)

Experimental: Circularly-polarised light was launched into several single-mode bow-tie fibres having a range of different numerical apertures (from 0·06 to 0·12), beat lengths, borosilicate dopant concentrations and geometries. The fibres were anchored at each end with epoxy between two glass slides, and the extension required to produce a 2π change in retardance was measured using a micromanipulator. The results are plotted in Fig. 1 for comparison with the theoretical curve. Also shown is Rashleigh's result,[1] suitably normalised, which was measured in a matched elliptical jacket[8] fibre. The agreement between theory and experiment is good, considering the number of approximations made in deriving eqn. 3. Moreover, the assumption that $\alpha(r, \theta)$ and $\nu(r, \theta)$ are proportional appears, within limits, to be valid.

Thus eqn. 3 predicts that the sensitivity of a polarimetric strain gauge is a property only of the dopant used (not its concentration) and the fibre beat length. Therefore the sensitivity can be increased by choosing a dopant which produces a larger change in Poisson's ratio ν.

Applications: In this Section we demonstrate how the properties of bow-tie fibres can be exploited in the simple strain-gauge shown in Fig. 2. A similar configuration has been used by Dziedzic to construct a variable fibre attenuator. Laser light is launched into a length L_1 of bow-tie fibre[3] which is tightly looped to form a polariser[4] at P. The length following the loop thus has only one mode excited (x-polarised) and delivers linearly polarised light to length L_2 of the same fibre. The splice S_1 was made such that the axes of birefringence in lengths L_1 and L_2 were rotated approximately 45° with respect to each other. A photograph of the splice, which was

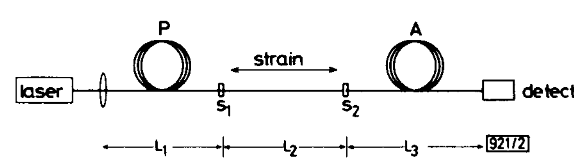

Fig. 2 *Simple strain gauge utilising jointed sections of the same bow-tie fibre*

Reprinted from ELECTRONICS LETTERS 18th August 1983 Vol. 19 No. 17 pp. 699-700

made with UV-curable adhesive,[5] is shown in Fig. 3. As both polarised modes are present in length L_2, the fibre can be used as a strain gauge utilising the stretching phenomenon.[1] The

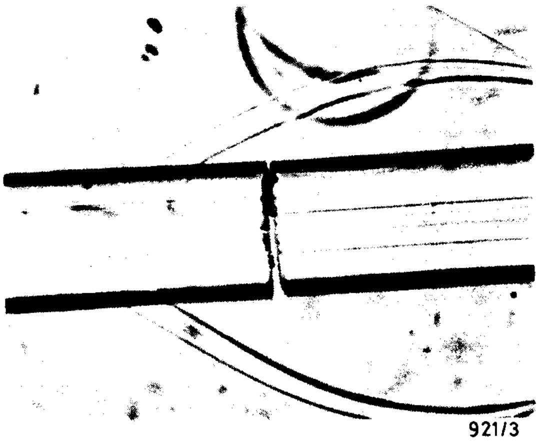

Fig. 3 *Splice between two lengths of the same bow-tie fibre using UV-curable adhesive*

Axes of birefringence are rotated approximately 45° with respect to each other

output of the strain gauge passes through a similar splice S_2 to length L_3 of the same fibre which polarises the light in the bend at A, and delivers the light to the detector D. On stretching the fibre, the birefringence of the fibre section between the polariser P and analyser A varies, resulting in a sine-squared light modulation.

A simple fibre strain gauge of length 1 m was found to have an 80% light modulation (π phase change) for $\sim$30 micro strain. The depth of modulation was limited by the accuracy of the orientations of the fibres in the splices.

Conclusions: It has been shown theoretically and verified experimentally that the variation in birefringence caused by stretching a high-birefringence fibre is the result of a mismatch in Poisson's ratio. A simple strain gauge has been demonstrated which exploits the polarising properties and high birefringence of bow-tie fibres. The example provides an insight into how bulk optical-polarising components and experiments can be emulated in bow-tie fibres by a series of jointed sections.

Acknowledgments: The authors would like to thank Dr. R. D. Birch and Dr. E. J. Tarbox for the high birefringence fibres used in the experiment and for useful discussions. A Research Studentship (MPV) was provided by British Aerospace plc and a Research Fellowship (DNP) by Pirelli Cable Company plc.

M. P. VARNHAM
A. J. BARLOW*
D. N. PAYNE
K. OKAMOTO†

29th June 1983

Department of Electronics
Southampton University
Southampton, SO9 5NH, Hampshire, England

* On leave from British Aerospace, Stevenage, Herts., England
† On leave from NTT, Ibaraki, Japan

References

1 RASHLEIGH, S. C.: 'Polarimetric sensors: Exploiting the axial stress in high birefringence fibres'. Presented at the First International Conference on optical fibre sensors, London, UK, 1983, Paper 4.1

2 VARNHAM, M. P., PAYNE, D. N., BARLOW, A. J., and BIRCH, R. D.: 'Analytic solution for the birefringence produced by thermal stress in polarisation maintaining optical fibres', *IEEE J. Lightwave Technology*, June 1983

3 BIRCH, R. D., PAYNE, D. N., and VARNHAM, M. P.: 'Fabrication of polarisation-maintaining fibres using gas-phase etching', *Electron. Lett.*, 1982, **18**, pp. 1036–1038

4 VARNHAM, M. P., PAYNE, D. N., BIRCH, R. D., and TARBOX, E. J.: 'Bend behaviour of polarising optical fibres', *ibid.*, 1983, **19**, pp. 000–000

5 DEVEAU, G. F., MILLER, C. M., and SMITH, M. Y.: 'Low-loss single-mode fibre splices using ultra violet curable cement'. Presented at the Sixth Topical Meeting of OFC, 1983, Paper PD 6.1

6 TIMOSHENKO, S., and GOODIER, J. N.: 'Theory of elasticity' (McGraw-Hill, New York, 1970, 3rd edn.)

7 SCHOTT GLASS CATALOGUE, Glass BK7

8 KATSUYAMA, T., MATSUMURA, H., and SUGANUMA, T.: 'Low-loss single-polarisation fibres', *Electron. Lett.*, 1981, **17**, pp. 473–474

9 DZIEDZIC, J. M., ASHKIN, A., STOLEN, R. H., and SIMPSON, J. R.: 'Tension adjusted inline optical fibre attenuator'. Paper TLF4, CLEO '83, Baltimore, USA, May 17–20th 1983