FABRICATION OF POLARISATION-MAINTAINING FIBRES USING GAS-PHASE ETCHING

Indexing terms: Optical fibres, Fabrication

A new fabrication technique for the production of high-birefringence fibres is described. The process is shown to produce fibres with a cross-sectional geometry which is close to the optimum predicted by stress analysis. As a result, fibres with extremely short beat lengths (0·55 mm at a wavelength of 633 nm) have been produced.

Introduction: Single-mode fibres which are able to transmit a stable, linear polarisation state are of interest for use in coherent detection systems and in fibre interferometers. Fibres in which very high birefringence has been induced, usually by introducing a large asymmetric stress distribution, are relatively immune to the external factors which disturb the polarisation state in conventional fibres. They are therefore able to sustain a single linearly polarised mode over long lengths.

High-birefringence fibres which utilise the stress-optic effect have been produced in basically three configurations: (*a*) the elliptical core/cladding type,[1] (*b*) the stressed elliptical-jacket type,[2] and (*c*) the side-pit type.[3] The fabrication method by which the cross-sectional stress-producing asymmetry is introduced is generally to generate a high thermal stress by employing materials with markedly different expansion coefficients and then either to machine-grind the preform[1] or to collapse an MCVD preform under slight vacuum[2] so as to produce ellipticity. Experience in our laboratories with both these methods gave somewhat variable results. Furthermore, a new analytic stress-analysis technique we have developed indicates that an elliptical cross-section does not make optimum use of the available expansion-coefficient mismatch. On the

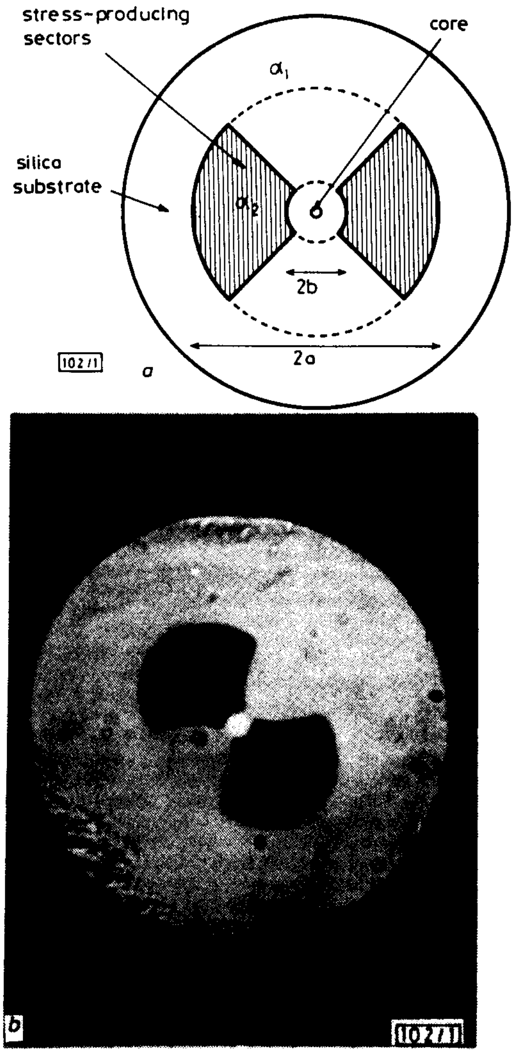

Fig. 1

a Calculated optimum cross-section geometry. The stress-producing sectors are highly doped to give a large expansion coefficient α_2

b Cross-section of bow-tie fibre manufactured by gas-phase etching

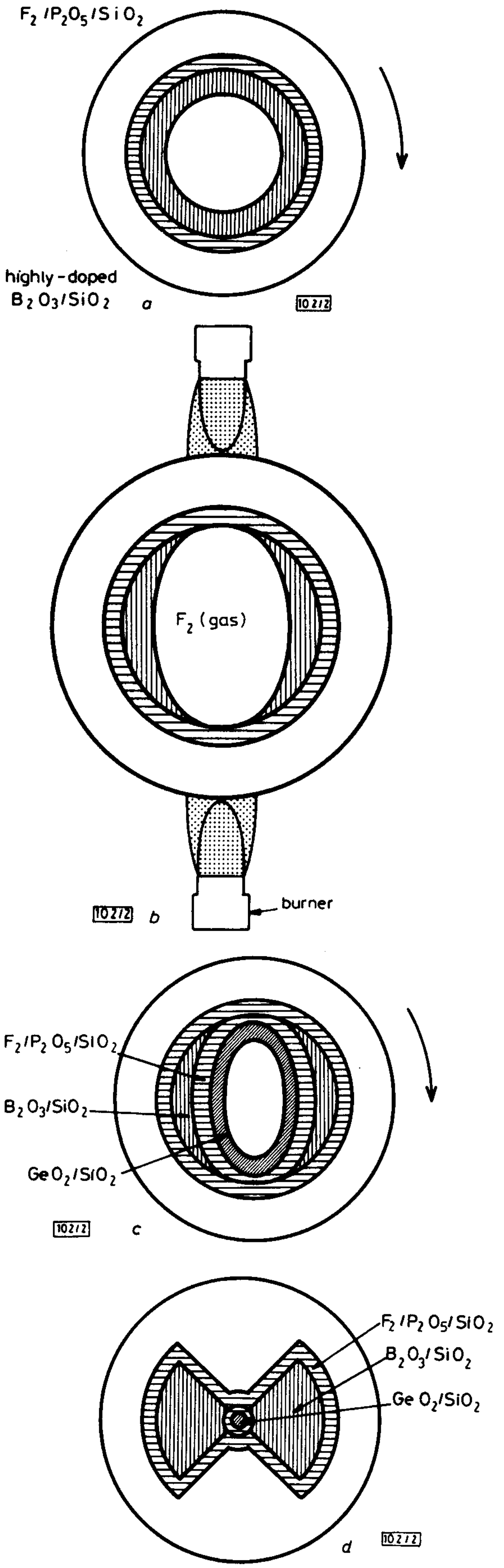

Fig. 2 *Schematic diagrams showing four stages of fabrication*

a Deposit
b Etch with flourine
c Deposit
d Collapse

Reprinted from ELECTRONICS LETTERS 25th November 1982 Vol. 18 No. 24 pp. 1036–1038

contrary, maximum asymmetric stress, and hence birefringence, results from a cross-sectional geometry resembling a bow-tie (see Fig. 1*a*).

We report here a new fabrication technique which is able to produce almost exactly the optimum fibre structure and is both simple and reproducible. The technique is capable of routinely producing low-loss fibre with beat lengths close to 1 mm at 633 nm, with some results as low as 0·55 mm.

Optimum fibre structure: Thermal-stress birefringence can be induced in a round silica fibre (expansion coefficient α_1) by embedding within it an asymmetric region of doped silica having a higher expansion coefficient α_2. An optimal cross-sectional shape exists for the stress-producing doped regions which maximises the anisotropic stress within the core for a given value of α_2 (i.e. for a given maximum dopant concentration). We have obtained an analytic solution for the stresses within the core which reveals that the optimum fibre structure has two 90° sectors of doped glass symmetrically disposed on either side of the core in a geometry which resembles a bow-tie (Fig. 1*a*).

Analysis further shows that:

(i) the outer radius *a* of the bow-tie (Fig. 1*a*) should be 0·75 of the fibre's outside diameter; larger values of *a* actually cause the birefringence to decrease

(ii) the inner radius *b* of the sectors should be as small as possible. However, this is normally limited by the requirement that the core be surrounded by a low-loss inner cladding of sufficient thickness to confine the optical power (*b* approximately equal to twice the core radius).

The bow-tie structure makes the most efficient use of the available expansion coefficient mismatch in producing maximum stress anisotropy. Analysis shows, on the other hand, that the more commonly used elliptical cross-section is considerably less efficient. Consequently, stresses are present which do not contribute to the birefringence and are therefore wasted. In practice, this results in a tendency for the highly stressed preform to shatter prematurely, and very high birefringence is more difficult to obtain.

Fibre fabrication: The fabrication technique utilises selective high-temperature etching, by a fluorine-liberating gas, of deposited layers from the inside wall of an MCVD preform tube. A glass substrate tube is rotated in a glass-working lathe and layers deposited by the normal MCVD process (Fig. 2*a*). First, a number of lightly doped fluorophosphorus buffer layers index-matched to silica are deposited. These are followed by layers of highly doped (20$^m/_o$ in the gas phase) borosilicate glass. The rotation of the lathe is then stopped and two burners positioned on either side of the tube are used to provide localised, diametrically opposed hot zones on the walls. These hot zones are traversed along the length of the tube while a fluorine-liberating gas, such as sulphur hexofluoride diluted with nitrogen, is passed down the bore (Fig. 2*b*). After several passes of the burners the borosilicate layers are etched completely away from two strips on opposite sides of the tube. The tube is then rotated again and further fluorophosphorus cladding layers conventionally deposited, followed by a germania-doped core (Fig. 2*c*). The tube is collapsed under slight positive pressure to ensure circularity of the core, and gives the geometry of Fig. 2*d*.

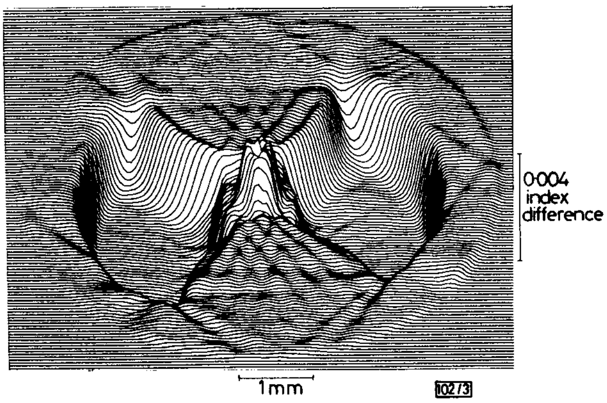

Fig. 3 *3-D refractive-index profile at bow-tie fibre preform obtained by tomographic spatial filtering*

The advantages of the technique are that: (*a*) it produces a cross-sectional geometry which closely resembles the optimum bow-tie structure with remarkable consistency; (*b*) the fabrication is a single-step process which does not require the preform to be removed from the lathe for regrinding or other operations, thus minimising the risk of fracture; (*c*) the maximum stress is only produced during the final stages of the preform collapse, when the stress-producing sectors converge on the core. Again the risk of shattering is minimised.

Results: The cross-sectional geometry obtained in a typical fibre is shown in Fig. 1*b*. Despite the unconventional shape, the geometry has been found to be remarkably reproducible. The close resemblance to the optimum geometry of Fig. 1*a* can be clearly seen. By close control of the relative dimensions of core, cladding, bow-tie regions and fibre outer diameter according to the guidelines given earlier, it is possible to optimise the geometry such that the expansion coefficient mismatch can be minimised for a given birefringence. This all but eliminates the risk of the highly stressed preform shattering during fabrication.

Fig. 3 shows the 3-D refractive-index profile of the preform obtained by the spatial-filtering tomographic reconstruction technique.[4,5] The core, slightly depressed cladding, bow-tie stress-producing regions and substrate are all visible. The F_2/P_2O_5-doped outer buffer layers are well matched to the silica substrate and are not visible.

Results obtained for polarisation beat-length measured at 633 nm are routinely less than 1·3 mm. The best result so far obtained is 0·55 mm, a birefringence which is some 60% higher than the best previously reported for stress-birefringent fibres. Typical losses are 10 dB/km at 633 nm, 3·6 dB/km at 850 nm and 1·8 dB/km at 1050 nm. Since no attempt has yet been made to minimise losses, improvements in this area are expected.

It is interesting to note that there have been two recent independent reports[6,7] of high-birefringence fibres having a geometry which resembles that obtained here, although not optimised according to our guidelines and therefore not having as high a birefringence. In both cases a different fabrication technique was used.

Conclusions: A new fabrication technique for polarisation-maintaining fibres has consistently produced bow-tie fibres with close to optimal geometry and extremely short beat lengths. The fabrication process is controllable, relatively simple, and, we believe, has significant advantages over other methods.

Acknowledgments: Acknowledgments are made to E. J. Tarbox and R. J. Mansfield for assisting with fibre fabrication, and to A. J. Barlow for helpful discussions. The work was supported by the UK Science & Engineering Research Council. A Research Fellowship was provided by the Pirelli General Cable Company (DNP), and a Research Studentship by British Aerospace plc (MPV).

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28th October 1982

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