THERMAL STRESS MEASUREMENTS IN OPTICAL-FIBRE PREFORMS USING PREFORM-PROFILING TECHNIQUES

Indexing terms: Optical fibres, Measurement

An analysis is presented of the effect of thermal stress on transverse refractive-index profiling of optical-fibre preforms. The theory leads to a new measurement technique for axial stress profiling.

Introduction: Transverse refractive index profiling of optical-fibre preforms is a well established technique which is important for quality control and the design of new optical fibres.[1–3] However, the effect on the measurement of thermal stress in the preform has never been quantified. This letter presents an analysis which leads directly to a new technique for measuring the axial stress profile in optical-fibre preforms.

Theory: Transverse refractive-index profiling is based on the measurement of the optical path length difference $\eta(\rho, \theta)$ between a ray traversing the preform at an offset ρ and direction θ (Fig. 1) and an equivalent ray in the index-matching fluid, where

$$\eta(\rho, \theta) = \int_{AB} (n(r, \psi) - n_0)\, dl \tag{1}$$

Here $n(r, \psi)$ is the refractive-index profile, AB is the path over which the ray traverses the preform (Fig. 1), and n_0 is the index of the surrounding medium. However, thermal stress in the preform in conjunction with the photoelastic effect causes the refractive index to become anisotropic. In this case the refractive-index profiles $n_x(r, \psi)$, $n_y(r, \psi)$, $n_z(r, \psi)$ seen by light polarised in the x, y and z directions is related to the unstressed isotropic index profile $n_i(r, \psi)$ and the stresses $\sigma_x(r, \psi)$, $\sigma_y(r, \psi)$, $\sigma_z(r, \psi)$ by[4]

$$\begin{aligned} n_x &= n_i - C_1\sigma_x - C_2(\sigma_y + \sigma_z) \\ n_y &= n_i - C_1\sigma_y - C_2(\sigma_z + \sigma_x) \\ n_z &= n_i - C_1\sigma_z - C_2(\sigma_x + \sigma_y) \end{aligned} \tag{2}$$

where C_1 and C_2 are the stress optic coefficients.

It is clear from eqns. 1 and 2 that the path length η depends upon the polarisation of the incident light. For example, if $\theta = 0°$, then η_y would be measured with y-polarised light and η_z would be measured with z-polarised light, where η_y and η_z are found by substituting for n by n_y and n_z in eqn. 1. After these substitutions, the evaluation of eqn. 1 is made using the following boundary conditions pertaining to long cylindrical bodies:[4,5]

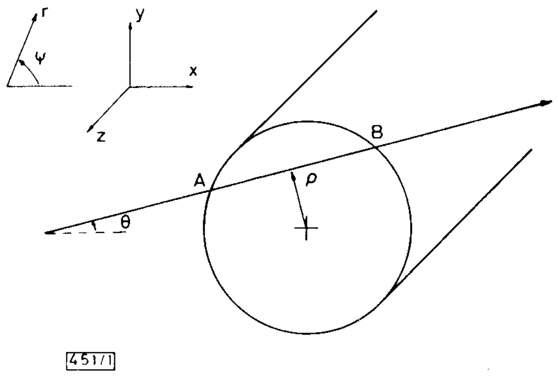

Fig. 1 *Co-ordinate system and path length AB in preform*

$$\iint \sigma_z\, ds = 0 \tag{3a}$$

$$\int \sigma_y\, dx = 0 \tag{3b}$$

$$\sigma_z = \sigma_x + \sigma_y \tag{3c}$$

Thus, for $\theta = 0°$, the nonzero terms in eqn. 1 become

$$\eta_y = \int_{AB} (n_i - 2C_2\sigma_z - n_0)\, dx \tag{4a}$$

$$\eta_z = \int_{AB} (n_i - (C_1 + C_2)\sigma_z - n_0)\, dx \tag{4b}$$

However, given that the choice $\theta = 0°$ was arbitrary, eqns. 4a and b are valid for any θ. Inversion of these equations therefore reveals that the apparent refractive index profiles n_{ze} and $n_{\theta e}$ measured using light polarised axially and perpendicularly to the preform axis, respectively, are given by

$$n_{\theta e} = n_i - 2C_2\sigma_z \tag{5a}$$

$$n_{ze} = n_i - (C_1 + C_2)\sigma_z \tag{5b}$$

The profile measured using unpolarised light is the average of $n_{\theta e}$ and n_{ze}, which from eqns. 2, 3c and 5 is equal to $(n_x + n_y)/2$, where n_x and n_y are the real profiles seen by x- and y-polarised light. Transverse refractive-index profiling therefore measures the average refractive index seen by unpolarised light travelling down the fibre. This is an important result, since, although it is not obvious, it has always been assumed in preform profiling.

Eqn. 5 forms the basis of a new measurement method for measuring the axial stress $\sigma_z(r, \psi)$ in optical-fibre preforms. Inspection reveals that the difference in the reconstructed profiles measured with light polarised axially and transversly to the preform axis is related, regardless of the transverse profiling technique used,[1–3] to the axial stress profile by

$$n_{ze}(r, \psi) - n_{\theta e}(r, \psi) = -(C_1 - C_2)\sigma_z(r, \psi) \tag{6}$$

Thus, two conventional preform profile measurements with the simple addition of a polariser set parallel and perpendicular to the preform axis can be used to obtain the stress profile.

Experiment: Fig. 2a shows the refractive-index profile of a circularly-symmetric preform, measured using the spatial-filtering technique[1] with the light polarised parallel to the axis of the preform. A similar measurement was performed using light polarised perpendicular to the preform axis. The preform

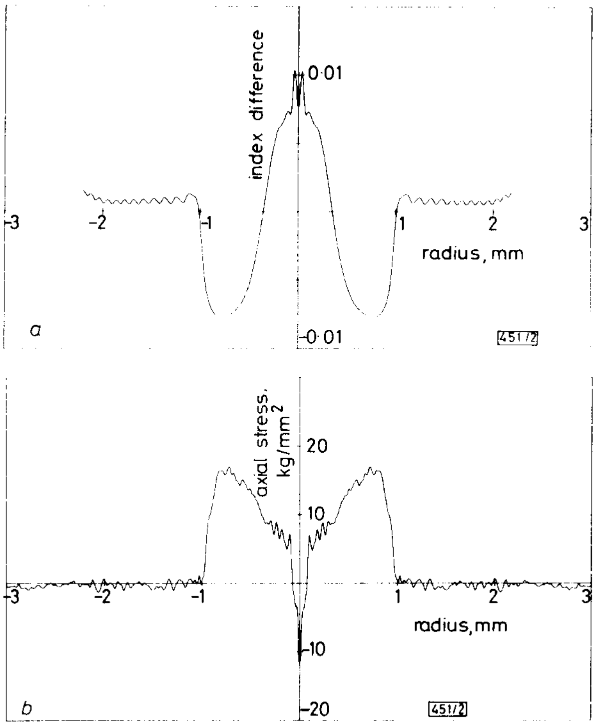

Fig. 2 *Refractive-index and stress profiles of monomode depressed-cladding fibre preform of radius 5·6 mm*

a Refractive-index profile
b Stress profile

Reprinted from ELECTRONICS LETTERS 6th December 1984 Vol. 20 No. 25/26 pp. 1034-1035

has a silica substrate, a P/F doped outer cladding, a B_2O_3 doped inner cladding and a GeO_2 doped core. The axial-stress profile, Fig. 2*b*, was obtained using eqn. 6 by subtracting the profile of Fig. 2*a* from the one obtained with orthogonally polarised light. The difference in stress optic coefficients $C_1 - C_2$ was taken as $-3{\cdot}54 \times 10^{-5}$ mm^2/kg. The measurement gives stress levels very much as expected and reveals that the depressed cladding has a tensile stress of approximately 15 kg/mm^2. This corresponds to an effective index difference $n_{ze} - n_{\theta e}$ of approximately 0·0005.

Discussion: The ability to measure axial stress in optical-fibre preforms is useful for the development of high birefringence and other specialist fibres, where the stress can shatter the preform. The conventional method using polarimetry is complex, and involves the reconstruction of the axial-stress profile from measurements of retardation.[6] The ability to measure axial stress using widely available refractive-index profiling equipment is therefore highly desirable. In particular, the measurements presented here can be extended to two-dimensional stress profiling of highly asymmetric preforms.

Conclusions: The effect of thermal stress on the transverse refractive-index profiling techniques has been analysed for the first time. Using unpolarised light, the reconstructed profile is equal to the average index seen by light travelling down the axis of the preform. The theory leads to a new measurement technique for axial stress profiling which uses widely available refractive-index profiling equipment.

Acknowledgments: The measurements described in this letter were made on the York Technology P101 Preform Profiler. We would like to thank York Technology for their co-operation. The preforms were supplied by R. D. Birch and E. J. Tarbox. A Research Studentship was provided by British Aerospace plc (MPV) and a Research Fellowship by Pirelli General plc (DNP).

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