ROUTINE CHARACTERISATION OF SINGLE-MODE FIBRES

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In single-mode fibres, the core diameter and refractive-index difference between core and cladding may be found from the widths of (*a*) the halfpower points and (*b*) the first minimum of the far-field radiation. The technique has been used to study the effect of heat treatment.

Introduction: Two of the fundamental parameters of any optical fibre are the core diameter $2a$ and the refractive-index difference Δn between that of the core (n_1) and cladding (n_2). In multimode fibres, the core diameter can be obtained by conventional optical techniques and Δn from measurements of the numerical aperture or of the refractive-index profile. However, in single-mode fibres, the effects of diffraction render such measurements more difficult. We present here a new and simple technique for determining $2a$ and Δn unambiguously, which can be used in a routine manner and by relatively unskilled personnel to assess fibres immediately after drawing. It involves only measurements of the far-field radiation pattern of the HE_{11} mode, which is easily observed[1] experimentally.

Far-field radiation of HE_{11} *mode:* We have calculated the normalised far-field distribution $\psi(r, \theta, \phi)$ from the Fraunhofer diffraction equation[2] and the approximate field equations derived by Snyder.[3] For the HE_{11} mode in structures having $\Delta n \ll n_1$ this distribution is

$$|\psi|^2 = \begin{cases} \left[\dfrac{U^2 W^2}{(U^2-\alpha^2)(W^2+\alpha^2)}\left\{J_0(\alpha) - \alpha J_1(\alpha)\dfrac{J_0(U)}{U J_1(U)}\right\}\right]^2 & \text{for } U \neq \alpha \quad (1a) \\[2ex] \left[\dfrac{U^2 W^2}{2V^2}\,\dfrac{1}{U J_1(U)}\{J_0{}^2(\alpha) + J_1{}^2(\alpha)\}\right]^2 & \text{for } U = \alpha \quad (1b) \end{cases}$$

where $V^2 = U^2 + W^2$, U, W are the arguments[3] of the Bessel and modified Hankel functions, $\alpha = ka\sin\theta$ is the normalised angle, $k = 2\pi/\lambda$, and θ = angle with the axis.

A convenient experimental parameter is the halfpower width of the main lobe, i.e. the output angle θ_h at which the far-field intensity has fallen to one-half of that at the central maximum ($\theta = 0$). Unfortunately, this measurement alone is not, of itself, directly useful. On the other hand, it may be shown from eqn. 1 that the normalised half-width $\alpha_h = ka\sin\theta_h$ is an unambiguous function of V. This relationship is indicated by curve *b* in Fig. 1. Thus, if the core radius a can be obtained in some other way, then, knowing θ_h, α_h (and hence V and Δn) may be calculated. Conversely, if V s known, then curve *b* gives α_h and measurement of θ_h gives the core diameter a.

The core diameter can sometimes be determined by an etching technique, but we have found that it can also be obtained from the full width of the main lobe in the far field. Thus it can be shown from eqn. 1, and also experimentally, that, in addition to the main beam, the far-field pattern exhibits a range of subsidiary peaks at angles and relative intensities which depend on a, n_1, n_2 and λ. Further, the angular width θ_x to the first minimum can be used in conjunction with θ_h to obtain V directly without any knowledge of a. Thus, like α_h, the ratio $\sin\theta_x/\sin\theta_h$ is also an unambiguous function of V and is given as curve *a* in Fig. 1 for the range of values most likely to be encountered in practical single-mode fibres. Thus, from the simple measurement of θ_x and θ_h, both V and a, and hence Δn, can be obtained. In the example illustrated in Fig. 1, it is assumed that the ratio $\sin\theta_x/\sin\theta_h$ is found experimentally to be 5·25, indicating, using curve *a*, that $V = 2{\cdot}14$. From curve *b* it can be seen that the corresponding value of $ka\sin\theta_h$ is 0·813 and from the measured value of θ_h it is possible to calculate a.

Experimental verification: The theoretical predictions have been confirmed on a number of single-mode fibres made by the technique[4] of homogeneous chemical vapour deposition. A Gaussian beam was launched into a 1 m length of fibre, slightly curved to inhibit the propagation of higher-order modes. Cladding strippers were also used.

The angular widths θ_h and θ_x were obtained by monitoring the far-field output pattern with an Integrated Photomatrix Ltd. Model 7000 scanning photodiode array. The values of θ_x were confirmed by taking photographs of the far-field pattern.

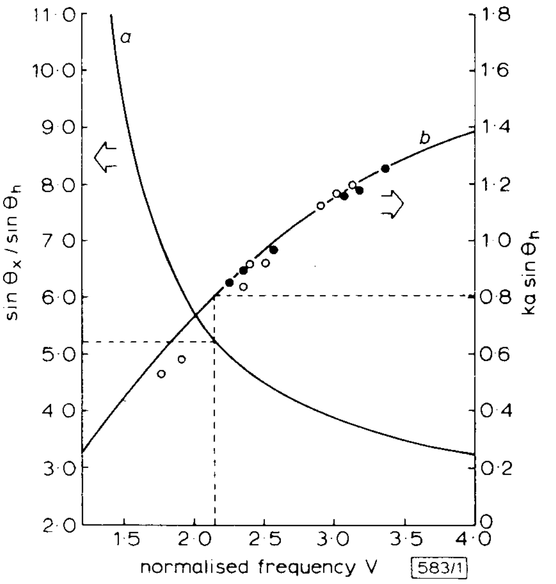

Fig. 1 *Variation of normalised half-intensity angle α_h and ratio $\sin\theta_x/\sin\theta_h$ with V*

The solid lines are calculated using eqn. 1, while the points were measured with fibres of core diameter 6·6 μm (○) and 8·1 μm (●) over the wavelength range 0·42–0·9 μm

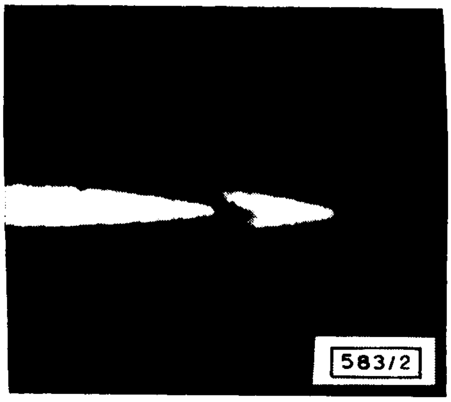

Fig. 2 *Far-field radiation pattern of HE_{11} mode*

Displayed on oblique screen to emphasise intensity minimum and subsidiary peak at edge of main lobe

Table 1 COMPARISON OF CORE DIAMETERS OBTAINED FROM FAR-FIELD PATTERN WITH THOSE MEASURED BY ETCHING

					Core diameter (μm) obtained from	
Sample	$\sin\theta_h$ (mean)	$\sin\theta_x/\sin\theta_h$ (mean)	V (mean)	Δn	Far-field measurements	Etching measurements
1	0·0211	5·38	2·10	0·00107	7·6	7·36×7·82
2	0·0385	5·14	2·18	0·00349	4·3	4·22×4·31

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The existence of the first zero in intensity is shown clearly in Fig. 2, where the far-field pattern is displayed on a screen held at an oblique angle to the fibre axis.

The core diameter was found experimentally by first etching with hydrofluoric acid, since phosphosilicate glass dissolves much more rapidly than the pure silica cladding. The cavity formed was then measured by an optical or scanning electron microscope. As a check, the fibre core diameter was estimated from the product of the preform core diameter and the ratio of the preform/fibre outside diameters. The agreement between the two methods was very good (within 2%).

Several single-mode fibres having core diameters ranging from 4 to 8·4 μm have been tested. In the first set of measurements, the angle θ_h was determined for two fibres whose core diameters of 6·6 and 8·1 μm were obtained by etching. By tuning the output from a Chromatix CM4 laser over the wavelength range 0·42–0·9 μm, the V values in these fibres were varied from 1·7 to 3·5. The experimental results are shown in Fig. 1 and are in excellent agreement with the theory.

In the second set of measurements, both θ_h and θ_x were measured for two fibres whose core diameters were again obtained by etching. For each fibre the angular measurements were made in ten independent experiments and the repeatability was within ±2%. A comparison with the far-field measurements is shown in Table 1. The cores were slightly elliptical and the figures in the final column denote the lengths of the major and minor axes. Again, the agreement between the two methods is excellent, particularly since the orientation of the fibre ends for the far-field measurements was not known.

Effect of heat treatment: One of the important factors in the application of optical fibres is their long-term stability and one of their advantages over coaxial lines is their ability to operate at higher temperatures. In a preliminary assessment of these factors in phosphosilicate single-mode fibres, we have used the technique described above to observe whether any diffusion of ions, or deformation of the core, occurs at elevated temperatures. A number of fibres have therefore been treated at temperatures of up to 1000°C. There were no discernible changes in core diameter or refractive index, nor in the attenuation, which was 4·7 dB/km at 0·85 μm. As far as thermal effects are concerned, these fibres therefore show great stability and are capable of operation at much higher temperatures than either coaxial lines or fibres made from compound glasses, such as the sodium borosilicates.

Conclusions: The core diameter and refractive-index difference can be obtained unambiguously from the far-field pattern of the HE_{11} mode in fibres of low V value. The technique is a simple one and can be applied to the routine characterisation of single-mode fibres under both production and laboratory conditions. To this end, universal curves are presented in Fig. 1, which apply to a wide range of fibres of low V values. The method has been used to show that with phosphosilicate single-mode fibres no change in a or Δn occurs at temperatures of up to 1000 C.

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W. A. GAMBLING
D. N. PAYNE
H. MATSUMURA

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

R. B. DYOTT

Department of Electrical Engineering
Imperial College of Science & Technology
London, England

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