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"OPTICAL FIBRE MEASUREMENTS"

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MODE PROFILING IN MONOMODE FIBERS

Two parameters which are essential for the design of monomode fibers and their associated systems are the normalized cut-off frequency V_c and the spot size w (or their equivalents). V_c determines the optical frequency and wavelength ranges for single mode operation and is related to the basic fiber properties a and Δ by

$$V_c = (2\pi a/\lambda_c)n_1(2\Delta)^{1/2}$$
$$= k_0 a N \qquad (1)$$

where a = core radius
λ_c = cut-off wavelength (see below)
$\Delta = (n_1 - n_2)/n_1$
n_1, n_2 = refractive indices in core, cladding
$k_0 = 2\pi/\lambda$
N = numerical aperture = $(n_1^2 - n_2^2)^{1/2} \simeq n_1(2\Delta)^{1/2}$

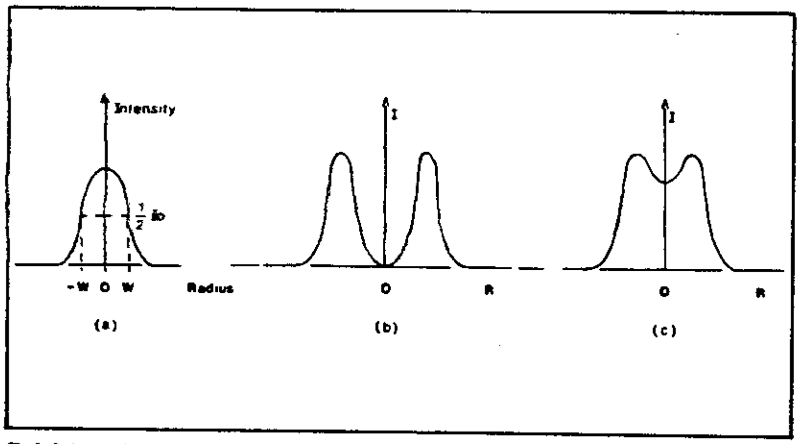

Fig. 1: Radial intensity distribution of the fundamental and second (b) modes. The combined effect of both modes is illustrated in (c)

If the operating normalized frequency becomes greater than V_c then additional modes appear and the dispersion increases catastrophically. On the other hand when V is too low the guidance properties of the fiber are impaired and the losses caused by bends and microbends rise markedly. Fibers are therefore designed to operate close to cut-off so that V_c must be known with reasonable accuracy.

The spot size w of the fundamental mode is defined as the radius at which the light intensity in the core is l/e times that at the center. It has a major influence on the losses arising at splices, connectors and launching, as well as at bends and microbends. In fibers where the radial intensity distribution, or mode profile, is close to Gaussian the loss at a joint becomes small even when V_c and N are different, if the spot sizes are made equal.

Measurement of Cut-Off

Because V_c depends on the shape of the refractive-index profile a more useful parameter is the wavelength λ_c below which the second-order, LP_{11}, mode begins to propagate.

Conceptually the simplest way to determine the cut-off point of a fiber is to observe the near-field distribution as the wavelength is changed. The output end face of the fiber is imaged by a high-quality lens onto a screen and in the monomode regime the image is a symmetrically circular spot with maximum intensity at the center (Fig. 1a). The intensity distribution of the second mode has a zero at the center of the pattern (Fig. 1b). Thus if the wavelength is decreased through cut-off, the peak at the center of the single-mode pattern becomes depressed as in Fig. 1c. The onset of this depression is difficult to detect by eye, and it is better to scan automatically across the magnified near-field pattern with a small detector. A further improvement is to employ a video camera in conjunction with digital processing.

In a fiber with a stepped refractive-index profile V_c = 2.4 and, having measured λ_c, either the core radius or the numerical aperture can be obtained from Equation (1) if the other is known. In practice the index is rarely constant in the core and the cut-off frequency may differ markedly from V_c. With a parabolic profile, for instance, V_c = 3.5.

Spot Size and Mode Profile

The width of the near-field pattern of a fiber to the l/e points can be obtained by scanning a small detector across the image, or by processing the output from a video camera (as in the measurement of λ_c). A more accurate method, which also avoids the problems of lens distortions, is to scan a small spot across the input face of a short length of fiber and collect the whole of the output on a fixed detector. The equipment is similar to that required for the determination of the refractive-index profile by the refracted near field technique. As the spot is traversed across the input end-face, the output from the far end of the fiber (instead of the refracted light intensity) is recorded. The continuous plot of the output gives a complete mode profile from which the spot size is easily obtained, or a measurement to only the l/e points may be taken.

An alternative to launching a small spot of light is to launch into a short piece of identical fiber and scan its output end across the face of the test fiber. The auxiliary fiber is separated from the test fiber by a small gap of approximately 4 μm filled with a drop of index-matching liquid. The spot size is obtained by noting the width corresponding to l/e of the maximum power coupled through the joint.

YORK TECHNOLOGY

TECHNOLOGY NOTE

The Equivalent Step Index Profile

In the ideal step-index monomode fiber a knowledge of the core radius and refractive difference enables V and w, and hence such factors as splice, bend, microbend and launching losses, to be calculated at any wavelength. In practice fabrication difficulties often cause a rounding of the profile between core and cladding and a pronounced central dip. Fibers made by vapour phase axial deposition (VAD) do not have a dip but there may be a spike at the edge of the core. Experiment shows that provided the departure from a stepped profile is not too large, the intensity distribution in the monomode region of operation remains close to Gaussian in shape, as in the ideal case. For any Gaussian beam it is possible to derive an equivalent step-index (ESI) profile which gives an almost identical intensity distribution. Thus the complex refractive-index profile of a real fiber can be replaced by an idealized step-index profile which closely describes the fiber performance.

The concept of the ESI profile is very useful because it enables one to easily calculate a wide range of fiber parameters with a reasonable degree of accuracy. Even when a central index dip is present, the predicted values of the loss factors referred to above, as well as the cut-off frequency and spot size, are in good agreement with those measured experimentally. Greater caution is necessary with dispersion and bandwidth calculations.

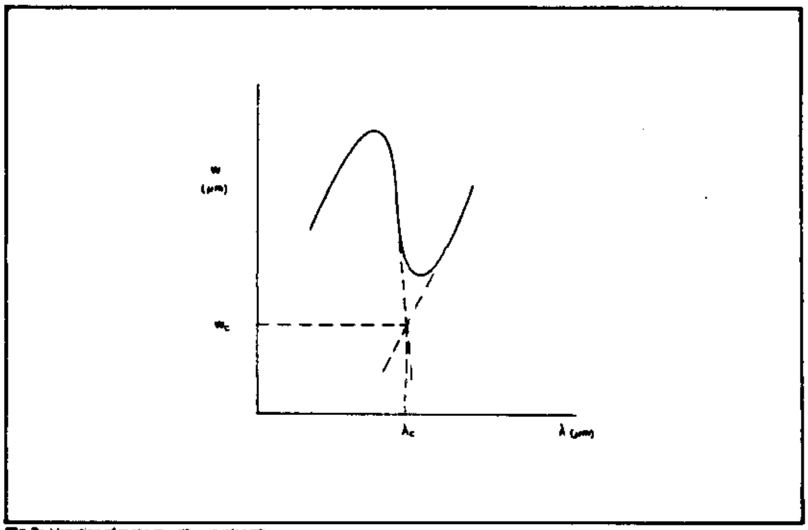

Fig.2: Variation of spot size with wavelength

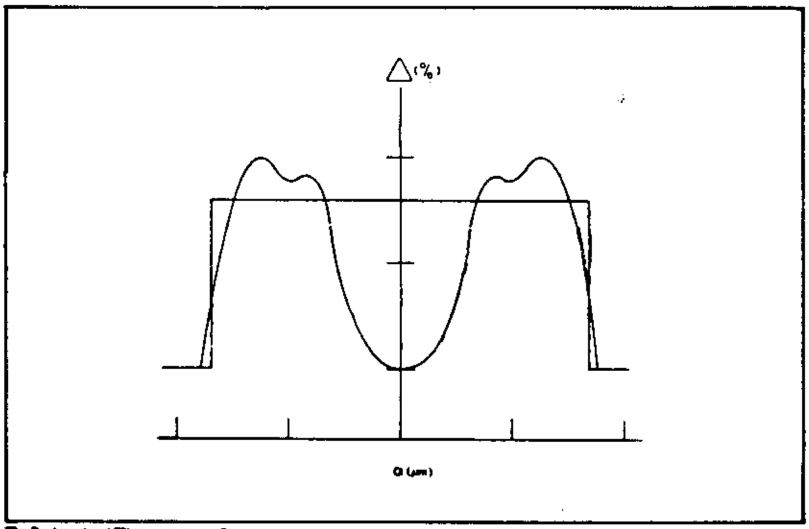

Fig.3: Actual and ESI monomode profiles

Determination of ESI Profiles

The far-field pattern of a monomode fiber consists of a large central peak and weak sidelobes. It has been shown that measurement of both the 3dB angular width of the main lobe and the width to the first minimum enables V, a, and Δ of the ESI fiber to be determined unambiguously. It is simple to obtain the 3dB width, but because the first sidelobe is 30-40dB down on the central intensity, the position of the minimum is more difficult to measure. However the technique is straightforward and requires no computation since standard universal curves[1] are available.

Another approach is based on the measurement of spot size over a range of wavelengths embracing λ_c. Any of the methods described earlier are suitable. For example, a small spot of light can be traversed across the input face and the total output recorded. Normally a series of filters, or a monochromator, is inserted between the light source and the fiber, and the scanning at different wavelengths is done sequentially. But results can be obtained more rapidly with a broad-band light source and a scanning Michelson interferometer at the output, in a form of Fourier transform spectroscopy. The type of result is shown in Fig. 2.

In the monomode region the spot size degreases as the wavelength is reduced. At cut-off the spot size rapidly increases owing to the appearance of the second-order mode, which is wider than the fundamental. Thus λ_c is easily determined. The equivalent core radius a_s is given by

$$w = 0.66\, a_s \quad (2)$$

from which the equivalent step numerical aperture is

$$N_s = 0.383\, \lambda_c / a_s. \quad (3)$$

The result may be checked from the slope $dw/d\lambda$ of the right-hand part of the curve since

$$a_s = 1.07\, [2.18 w_c - \lambda_c\, (dw/d\lambda)]. \quad (4)$$

An example of the measured profile and its ESI equivalent is given in Fig. 3.

A simpler method requiring a measurement of λ_c and spot size at only a single wavelength is as follows. The spot size is measured in the monomode region at a convenient wavelength λ_1. It is assumed that the numerical aperture is independent of wavelength so that the step equivalent V_s is related to wavelength by $V_s\lambda = V_c\lambda_c$.

The step equivalent at λ_1 is therefore given by

$$V_{s1} = 2.4\, \lambda_c / \lambda_1 \quad (5)$$

The cut-off wavelength is also determined and the equivalent core radius a_s is given by

$$a_{s1} = w\sqrt{2}\, [0.65 + 1.62\, V_{s1}^{-1.5} + 2.88\, V_{s1}^{-6}]^{-1} \quad (6)$$

Δ and N can then be obtained from Equation (1).

1. W.A. Gambling, D.N. Payne, H. Matsumura and R.B. Dyott; Determination of core diameter and refractive index difference in single-mode fiber by observation of the far-field pattern; Microwaves, Optics and Acoustics 1 p.13; 1976.

Other Methods

Most of the techniques discussed above for obtaining λ_c, w and the ESI parameters involve measurements on the mode profile in some way. It is not possible to describe all alternative methods but two examples, both based on fiber attenuation, will be outlined.

In the first, the transmission loss of a short length of fiber is determined for a range of wavelengths around cut-off. One set of measurements is made in the straight fiber and the second after a bend of a few centimeters radius is introduced. When the ratio of the readings is plotted, the resulting curve of relative attenuation versus wavelength rises sharply near λ_c. This simple method of obtaining λ_c relies on the fact that just above cut-off the second (LP_{11}) mode is launched but is only weakly guided. The bend in the second measurement causes it to be radiated, producing a high loss compared with that in the straight fiber. For $\lambda > \lambda_c$ the loss is unchanged by bending because the fundamental is far from its cut-off point. Well above cut-off the second mode is less affected by a bend since it is more tightly bound, and the attenuation ratio falls once more to unity.

The accuracy in the value of λ_c obtained depends on the amount of microbending present in the fiber. Microbends cause strong radiation of the LP_{11} mode even in the straight fiber and the observed λ_c is too low. In fact the weak guidance of the LP_{11} mode just above cut-off causes problems with most measurement techniques involving a wavelength scan through λ_c.

The next method enables the spot size to be found using the equipment required for the cut-back type of measurement. The only modification is the insertion of a variable aperture lens between the light source and the fiber. After the attenuation readings have been taken, the output power from the short fiber is recorded as the angular launch aperture is reduced gradually from its maximum value. Provided the input beam is Lambertian and $\lambda > \lambda_c$ the variation of power with angle, $P(\theta)$, enables the spot size w_0 to be determined from

$$\ln [1 - (P(\theta)/P_1)] + 2 \sin^2\theta/\sin^2\theta_0 = 0 \quad (7)$$

where $\sin\theta_0 = \lambda/\pi w_0$ and P_1 is the asymptotic value of $P(\theta)$ when $\sin\theta >> \sin\theta_0$.

In this calculation w_0 is the spot size to the $1/e^2$ intensity. By measuring w_0 over a range of wavelengths the ESI core radius a_s, as well as λ_c, may be obtained by fitting the results to the curve

$$w_0 = a_s [0.65 + 0.434 (\lambda/\lambda_c)^{1.5} + 0.0149 (\lambda/\lambda_c)^6] \quad (8)$$

It is clear from the last method that care has to be taken in the use of the term "spot size". The simplest practical definition is the radius to one half (−3dB) of the maximum intensity. Some authors refer to the radius where the field amplitude ($\propto$ [intensity]$^{1/2}$) is 3dB down while others, as in the above method, choose the −6dB radius.

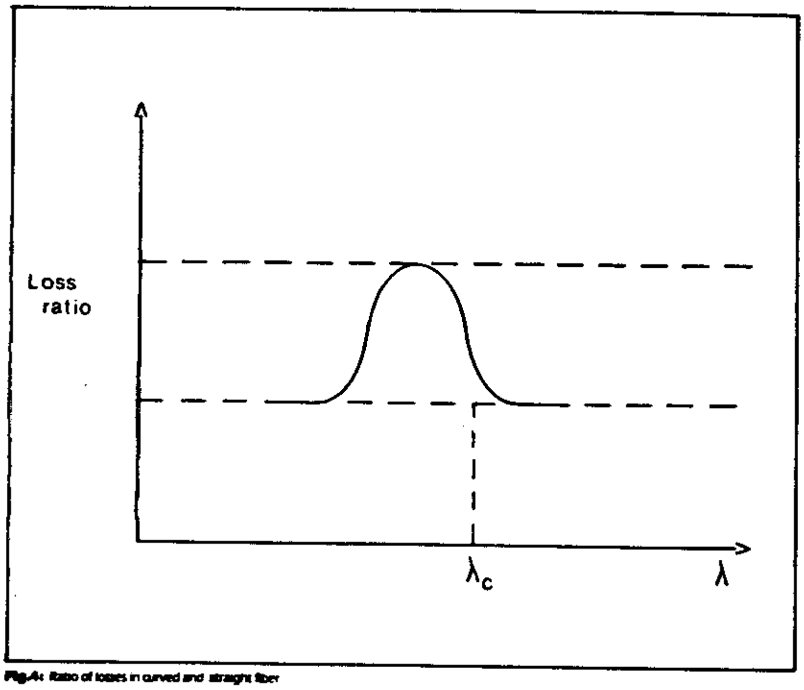

Fig.4: Ratio of losses in curved and straight fiber

Final Comment on the ESI Profile

The equivalent step-index profile is based on the observation, confirmed theoretically, that the mode profile remains a close approximation to a Gaussian shape up to surprisingly large departures from a stepped refractive-index profile. This is extremely convenient, since it implies that the actual index profile does not have to be known accurately. Furthermore, small variations along the length of a fiber are not important provided the mode profile, and hence the ESI profile, does not change. Calculations of the transmission parameters are immensely easier with the ESI profile than with a real index profile which may contain a central dip, ripples, rounding at the edges, and variations along the fiber.

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END FACE INSPECTION

Inspection of the end face of an optical fiber can provide very useful information about some of the basic fiber properties. When the far end of a short length is illuminated by a small light source the various regions such as the core, cladding and substrate glass can be clearly seen. Simple visual inspection through a microscope, either directly or via a video camera, can indicate immediately whether the core and cladding are appreciably non-circular or eccentric, and whether the end surface is reasonably flat. The core diameter and cladding thickness can be measured in the same way. In fact, for uniform mode excitation at the input to the fiber, the light intensity at any point on the output face is a measure of the local refractive index, which explains why the various regions in the cross-section show up so clearly.

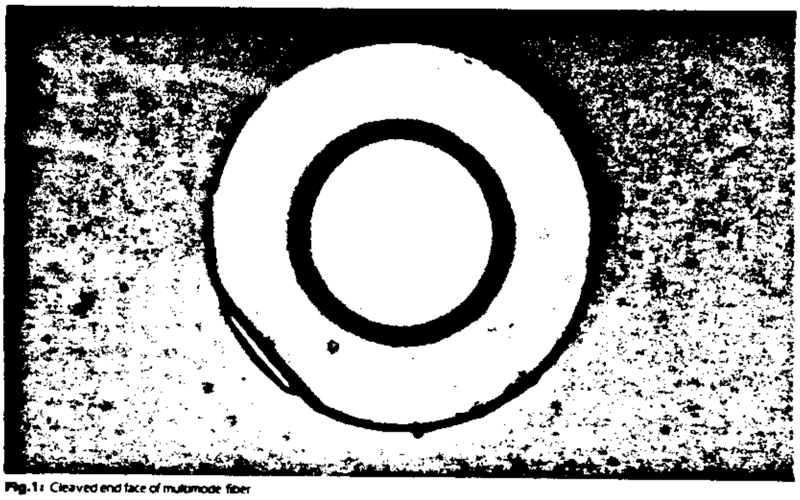

Fig. 1: Cleaved end face of multimode fiber

Why make end-face measurements?

Production fibers have to be of fixed dimensions and the above parameters are normally measured as a matter of routine. Standardization of the geometry is essential in order to achieve low coupling losses, particularly when jointing different fibers from the same manufacturer or fibers from different manufacturers.

Both the core diameter and the concentricity of the core within the overall structure must be tightly controlled: to ensure joint, or connector, losses of less than 0.2dB requires a lateral offset between the cores of graded-index multimode fibers of less than 2 μm. In monomode fibers the precision has to be improved considerably and a joint loss of 0.2dB corresponds to a concentricity error of less than about 0.5 μm. In large-core fibers and short-distance links the requirements can be relaxed.

Cladding thickness and uniformity must also be carefully checked. Some of the energy carried by the fiber lies outside the core, and the cladding must be of purity comparable to that of the core over a distance of at least a few micrometers in multimode fibers and 20-30 μm in monomode fibers. Furthermore, substrate tubes contain a small but significant quantity of water, which can diffuse into the cladding and core at the high temperatures used in fiber fabrication. OH ions cause an increase in attenuation and must be prevented from diffusing into the active part of the cladding; to achieve this, the thickness of deposited cladding is increased beyond the values given above. To keep costs down, however, the number of layers needs to be kept to a minimum. Thus, the cladding thickness is routinely monitored. In the MCVD process it is typically made 15-20 μm in multimode fibers and 15-25 μm in monomode fibers, though the precise values vary quite widely in practice since they depend strongly on the numerical aperture.

International discussions on the standards to be adopted are still continuing, but it may be useful to refer to the proposals of the CCITT (International Consultative Committee for Telegraph and Telephone). As an example, the recommendation for graded-index multimode fibers is that the core diameter should be 50 $\mu m \pm 6\%$, the overall diameter 125 $\mu m \pm 2.4\%$, outside non-circularity $< 2\%$, core eccentricity $< 6\%$ and non-circularity $< 6\%$.

In order to obtain both high launching efficiency and low joint losses, it is important to ensure that the fiber end face is flat and cleaved accurately perpendicular to the axis. This is particularly crucial in monomode fibers.

End-face Inspection

A photograph, taken through a microscope, of a short fiber illuminated from the far end is shown in Fig. 1. The core has the highest refractive index and appears brightest, while the cladding is dark. The refractive index of the substrate lies between those of the core and cladding and it is of medium brightness. By traversing the microscope, or by making measurements on the photograph and applying the necessary scaling factors, the diameters of the core, the cladding, the fiber, and the silicone coating (if present) can be obtained, and the various eccentricities and departures from circularity deduced.

Such a simple visual technique is very convenient for casual inspection and assessment of a fiber, but it is slow and tedious if quantitative results are required. It is also prone to subjective errors on the part of the operator since the different boundaries are not always clearly defined.

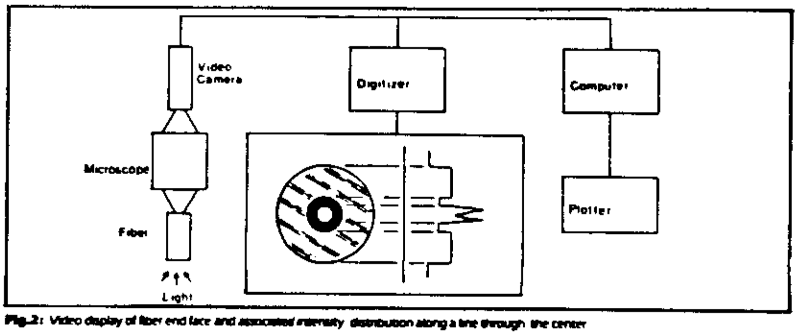

Fig. 2: Video display of fiber end face and associated intensity distribution along a line through the center

Automatic end-face measurements

A considerable improvement in speed, flexibility and accuracy is obtained by coupling a video camera and associated analyzing system to the microscope, as illustrated in Fig. 2. The optical data can now be acquired, digitized, processed, analyzed, then displayed. If the signal voltage is made proportional to the light intensity of the optical image seen by the video camera, and scanning is performed along a series of parallel lines, then the intensity information of each line scan can be digitized and recorded. By programming a computer to analyze the data, the diameters of core, cladding and outer coating are readily obtained. Further processing of the information can yield the degree of non-circularity and the core eccentricity.

A distinct advantage of conducting end-face measurements automatically is the speed, repeatability, and relative ease with which the results are presented. This is particularly relevant in an industrial environment, where quick feedback of information can produce a considerable saving of money and materials. Automated end-face measurements also increase the precision of the results obtained. Subjective errors in judgement are eliminated, and a larger number of data points can be used to calculate ellipticity than is generally possible with a manual method. The automatic equipment is able to detect ellipticities that are not noticeable by visual inspection.

With multimode fibers the method can also provide a rapid qualitative indication of the refractive index profile. The plot of the intensity distribution along a particular line scan gives an indication of the refractive-index distribution across the fiber. As shown in Fig. 2., all the principal features – such as the central dip and ripples in the profile – can be obtained with good resolution. The accuracy of this plot as a measure of index profile will, however, depend on the launching conditions and on whether any corrections for leaky mode propagation are necessary.

For monomode fibers the same measurement procedures may be followed but a higher degree of spatial resolution is required at the core boundary, since the core diameter is 10 μm or less. Furthermore, when the number of modes propagating is small, the near-field intensity is no longer closely related to the refractive index.

In fibers designed to have a high birefringence, strong asymmetries are deliberately introduced during manufacture. Boundary scanning and plotting are essential to check whether the required ellipticity has been attained.

Flatness and angle of the end-face

Examination by microscope can give an indication of the end face flatness, depending on the depth of the field of view. Indeed, by scanning the microscope across the fiber and noting the adjustment necessary to bring the surface back into focus, one can, in principle, plot the topography of the entire end face. However, such a procedure is tediously slow without an automatic focusing system. In addition, the resolution available is normally inadequate; an end-face angle of 1 degree relative to the perpendicular from the axis corresponds to a difference in height across a 125 μm diameter of only 2 μm.

Accurate assessment of surface flatness requires an interference microscope and measurement on the resulting fringe pattern but this is very time-consuming and is not necessary for most practical purposes.

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The FCm1300 End Face Inspection Module

The FCm1300 and FCm1310 modules are designed to provide qualitative and quantitative information on the end face of a fiber which has been prepared for further analysis.

Serious irregularities in the end surface may be introduced by the cleaving operation. If so, then these can alter the intended launch conditions, or they may cause the radiation pattern to become unacceptably irregular on the receive (output) end of the fiber. Early inspection can identify such faults and the fiber can be taken out and re-prepared for meaningful characterization.

In the FCm1300 and FCm1310 the measurements are conducted with the aid of a video camera. The camera can be made to receive radiation from either the launch end or the receive end of the fiber. This radiation will in general be a mixture of light reflected from the fiber end-face and of light which has been transmitted through the fiber. A number of light sources are distributed throughout the system to provide the desired effects.

The magnification of the optical system has been chosen so that a 5 μm monomode core will provide a 1 cm diameter display on the monitor screen. Any alterations in the optics or in the lighting conditions are effected by the system controller.

With the FCm1310 the video camera data is converted into digital information and is then analyzed by the system controller. From this data, the core, cladding and coating dimensions; the shape of the core and cladding; and the concentricity can be determined. Hence it is possible to measure the ellipticity, or departure from circular shape, and the FCm1310 gives quantitative assessment of this factor. When the camera is set to look at the receive end of the fiber, the optics may be set to take up the far field pattern. In this case the usual far field information may be utilized, for example to determine the fiber NA. In general this is not necessary, since it can be obtained from the index profile information set. But some users prefer to have both methods available.

Human Engineering and Economic Considerations

The FCm1300 and FCm1310 are best used as an integral part of a more general measuring system. In this context they serve to check the suitability of a fiber for characterization by the other modules and prevent time being wasted on unsuitably prepared fibers. The end-face analyzer also generates the geometry and/or far-field information set, all without the usual separate and often complicated setting up procedure.

SPECTRAL ATTENUATION

Energy is lost from a light signal as it propagates along a fiber. The intensity gradually decreases and eventually becomes so small that noise in the detector circuit begins to cause errors and distortion in the receiver output. To prevent this condition being reached the signal has to be amplified, or regenerated, in a repeater. In a long-haul communications link the distance between repeaters should be as large as possible and the fiber attenuation must therefore be minimized. For other applications the requirements are not as stringent but in all cases the loss has to be carefully controlled. Quality checks prior to installation are therefore essential.

The rate of attenuation depends on various intrinsic factors – the materials used and their purity, fiber design and wavelength – as well as external factors such as bends and pressure, coating and cabling techniques. When the transverse intensity distribution is uniform along the length then the power P(z) at any point is related to the input power P_1 by

$$P(z) = P_1.\exp(-\alpha z)$$

assuming that the power loss coefficient or transmission loss, α is independent of position. In a fiber of length L the loss is usually normalized to a length of 1 kilometer and is expressed as $(10/L).\log[P_1/P(L)] = 4.3\ \alpha$ dB/km.

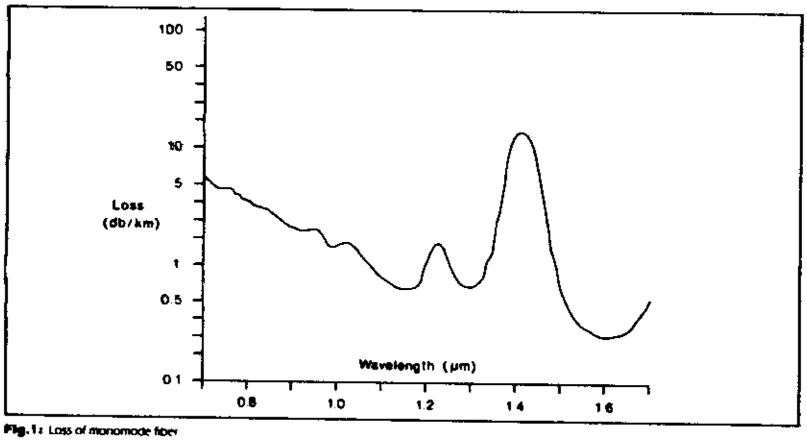

Fig. 1: Loss of monomode fiber

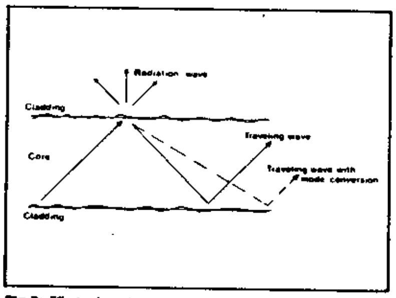

Fig. 2: Effects of rough core boundary

Intrinsic Losses

The intrinsic loss mechanisms can be broken down into (i) those producing a scattering of energy out of the guided modes and (ii) absorption.

(i) Scattering

During fabrication a fiber is rapidly cooled from the liquid state to a solid as it emerges from the hot zone in the drawing furnace. The density of a liquid is not uniform but contains minute variations of a magnitude and scale depending on the absolute temperature. When the fiber solidifies these density variations are frozen in, producing corresponding refractive-index variations in the core of the fiber which then scatter propagating light. Because the regions of inhomogeneity are small compared with the optical wavelength λ (of order 1 micrometer) the mechanism is that of Rayleigh scattering, where the power lost is proportional to λ^{-4}, and hence varies strongly with wavelength. In high-quality fibers, Rayleigh scattering is the dominant mechanism below 1 μm and the region of the curve between wavelengths 0.7 and 1.0 μm in Fig. 1 arises almost entirely from this process.

Fig. 2 illustrates another type of scattering that can occur if there are perturbations in the core/cladding boundary. These perturbations reflect rays randomly, causing those remaining in the core to be at a different angle from the incident angle (mode conversion) while those deflected out give rise to a waveguide scattering loss. The latter has only a weak wavelength dependence and is therefore easily distinguished from Rayleigh scattering. In graded-index fibers a similar scattering is caused by inhomogeneities in the refractive-index profile.

(ii) Absorption

Silica is chosen to form the principal component of telecommunication fibers because it is the material having the lowest absorption loss in the visible and near infra-red regions of the spectrum. The nearest absorption regions are those due to electronic transitions in the ultraviolet, and the vibrational resonance of the Si-O bond in the infra-red (at 9 μm). Other oxides which are commonly added to silica to produce changes in refractive index, namely those of germanium, phosphorus and boron, have similar IR resonances at 11, 8 and 7.3 μm respectively. The tail of the UV absorption reaches into the visible region but it contributes a lower loss than scattering. However, the wings of the IR absorptions can have a significant effect at wavelengths down to about 1 micrometer, and become dominant between 1.4 and 1.6 μm depending on the additive materials.

While impurity levels of 1 part in 10^9 are possible with several CVD fabrication methods, it is quite difficult to remove all traces of water. The OH radical has a fundamental vibrational absorption at 2.72 μm with harmonics at 1.38, 0.95 and 0.72 μm, and combination overtones of the Si-OH bond appear at 1.24, 1.13 and 0.88 μm. These may all contribute to the general level of loss in the wavelength region of interest, depending on the amount of OH present. Some of these lines can be seen in Fig. 1.

YORK TECHNOLOGY

TECHNOLOGY NOTE

Extrinsic Sources of Loss

In a straight, well-made fiber unaffected by external influences the loss components are those described above. In practice, a certain amount of additional attenuation can be caused by excessive bending, or by incorrect application of the protective primary and secondary coatings causing a microbending loss.

Monomode and Multimode Fibers

The intrinsic loss mechanisms are of the same general type in both monomode and multimode fibers. One difference is that more power is carried in the cladding of monomode fibers so the region in the vicinity of the core must be of higher purity out to a radius of 20 to 30 μm. In a multimode fiber the mode conversion induced by bends and microbends can cause power from a guided mode to be coupled into other guided modes as well as into radiation modes. The increased loss is therefore accompanied by a small change in bandwidth, which may be increased or decreased depending on the propagation conditions. In a monomode fiber, however, only a power loss occurs since there is only one guided mode.

Measurement of Absorption Loss

The energy lost by absorption as light propagates down a fiber is changed to thermal energy, and produces a small but detectable rise in temperature. Calorimetric techniques have been developed for measuring this temperature change (hence the absorption loss) but they suffer from systematic errors and it is difficult and time-consuming to achieve a high degree of accuracy. Fortunately such measurements are rarely necessary.

Measurement of Scattering Loss

The scatter loss can be obtained by injecting a known amount of power into a fiber and measuring the energy radiated out through the cladding. In a typical method the test fiber is mounted inside an integrating sphere (or cube) whose inner surface should ideally be of perfectly diffusive material having high reflectivity. To prevent light scattered out of the core becoming trapped in the cladding, the uncoated fiber must be placed in a liquid having a refractive index slightly higher than that of the cladding. The energy density in the integrating sphere is indicated by a sensitive detector set into the wall. In a simpler method, the fiber is placed between two large-area detectors again with index "matching" liquid. A knowledge of the scattering level is only necessary in limited cases – to get an idea of the extent of waveguide imperfections, for example.

Total Loss

For the great majority of applications it is the total transmission loss of a fiber that is of greatest interest. This could be obtained by measuring the absorption and scattering losses separately and adding them together, but fortunately there are other methods available that are much more accurate and less time consuming.

Before describing measurements of total loss, however, we should give some consideration to launching conditions.

Launching Conditions

In a monomode fiber only one bound mode can be launched into the core. All the transmitted energy is contained in this one mode; unbound modes lose energy and are soon radiated. The radial energy distribution pattern thus remains unchanged along the whole length of the fiber. External effects such as bends, microbends and any cladding attenuation may induce a change in magnitude but cannot change the guided mode pattern.

In multimode fibers, on the other hand, the situation is not so simple. It is possible to have a wide variety of launching conditions, ranging from that giving only a single mode, to full excitation of all possible modes. The measured attenuation can be considerably influenced by the input mode distribution, depending on many factors including the length over which the measurement is made.

As the modes propagate various forms of interaction can occur. Firstly, as stated earlier, bends, microbends and other inhomogeneities can cause a coupling of energy from one guided mode to other guided modes, as well as to radiation modes, with a resulting energy loss. High-order modes are more susceptible to this form of attenuation and to differential mode attenuation caused by an impure cladding. Secondly, when a graded-index multimode fiber is excited by a source which completely fills the numerical aperture and covers the whole of the core cross-section, a great many leaky modes are excited, most of which are radiated away in a distance of a meter or so. The measured loss over the first few meters may therefore be much higher than in the rest of the fiber.

Over a sufficient length of fiber, a balance is established between the various mode conversion and differential mode attenuation mechanisms, and an equilibrium mode distribution is attained. It is important, therefore, that the launching conditions should be properly defined and carefully controlled if consistent results are to be achieved.

Launching the Equilibrium Mode Distribution

In order to predict correctly the overall loss of jointed lengths it is essential to conduct attenuation measurements with a good approximation to the equilibrium mode distribution.

One of three methods is generally adopted. The most obvious is to launch into the test fiber through a piece of indentical fiber which is sufficiently long to ensure the equilibrium distribution is attained. As well as the inconvenience, a major disadvantage of this method is that the extra length reduces the power being launched into the test fiber and hence lowers the measurement accuracy.

A second technique is to launch through a mode scrambler, which is usually a short length of fiber subjected to microbending via a comb-like pressure structure. However, this produces a rather unpredictable mode distribution, which for the best results must be measured by scanning the output far-field pattern.

The third method involves controlling the input beam so that it is of uniform transverse intensity, covers 70% of the fiber core and fills 70% of the maximum numerical aperture of the core. This limited beam optics (or limited phase space) method is being considered for adoption by the US Electronics Industries Association, since the launching conditions are standard and reproducible. The distribution may not be absolutely identical with the equilibrium state for all fibers, but the approximation is very good and produces excellent results.

Measurement of Total Attenuation – the Cut-Back Method

In principle the simplest method of measuring fiber attenuation is to use a known length of fiber, launch into it a measured amount of light and then detect the output. In practice, it is difficult to determine accurately how much light actually enters the fiber and there will also be an unknown leakage from the first few meters. The problem can be solved quite simply by the arrangement shown in Fig. 3.

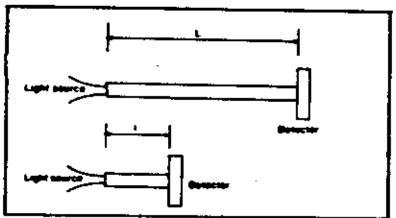

Fig. 3: Loss measurement by cut-back method

A suitable but unquantified amount of light is launched into a length L of fiber and the output P(L) is measured at the far end. With the launching conditions unchanged the fiber is cut back to the few (l) metres from the source and the output power, P(l), again measured. The total attenuation in dB over the length (L-l) is then

$$A = 10.\log [P(l)–P(L)]$$

and the loss per unit length is

$$a = 10/(L-l) .\log [P(l)/P(L)] \text{ dB/km}$$

In addition to accurate control of the light distribution and position at launch, a number of other precautions are necessary with the cut-back method. The launch optics must be stable, especially with monomode fibers, and the input light intensity must not change during the measurement; alternatively the source can be monitored and a suitable correction made. All radiation must

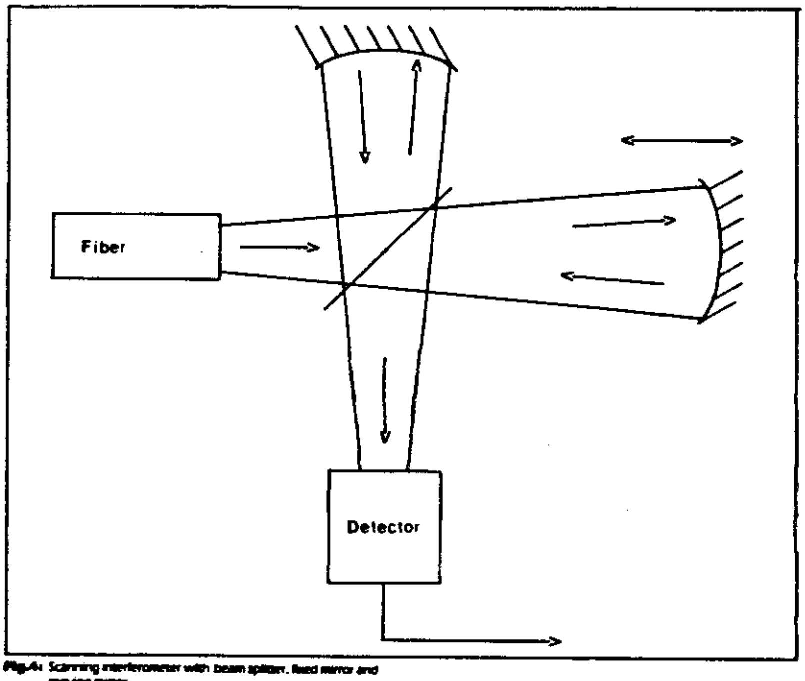

Fig.4: Scanning interferometer with beam splitter, fixed mirror and moving mirror

be removed from the cladding at the input end of the fiber, which can be done by immersing it in index-matching liquid in a cladding stripper. The ends of the fiber should be flat and perpendicular to the axis to ensure the correct mode distribution at the input. Non-reflective coupling to the detector is helped by placing a drop of index-matching liquid on the detector surface, which also helps to smooth out optically any roughness on the fiber end-face. The spatial variation of detector response must be small over the region of interest and the same detector area must be used for both sets of measurements. The accuracy and sensitivity are increased by chopping the input beam and using a phase-sensitive detector or by numerical signal averaging in a computer.

Another practical consideration is that if an uncabled fiber is wound tightly on its supporting drum then additional, variable microbending losses will be introduced and the results obtained will not be characteristic of an unstressed fiber. Any winding stresses should therefore be relieved.

One disadvantage of the cut-back method is that it is destructive. But the residual length required for the second measurement can be relatively short – only a few meters in a total length of several kilometers – and the measurement accuracy is very high: better than 0.1db/km.

Spectral Loss Measurements

When the spectral variation of loss is required it is necessary to measure the output power from the length L at all wavelengths before cutting back and repeating the wavelength scan. The reason for careful control of source and launching stability is now clear. Normally a white-light source is used which may be a tungsten filament or a high-intensity arc lamp. Continuous wavelength selection can be provided by launching into the fiber through a motor-driven monochromator, while rapid selection of discrete wavelengths may be obtained by mounting interference filters on a rotating wheel.

Differential Mode Attenuation

For some applications of multimode fibers a knowledge of the averaged attenuation over the whole set of propagation modes is not sufficient and it is desirable to investigate the behaviour of the individual mode groups. This is easily implemented in the cut-back method since a given mode group is excited by launching a narrow beam at a particular radial position. The detector can be allowed to collect all the output radiation, or, alternatively, it can be provided with a suitable aperture. The loss measurements are carried out in the normal way for various radial positions and the attenuation of the different mode groups is obtained.

Fourier Transform Techniques

The conventional methods of loss measurement so far described are very inefficient in the use of processing time since light of only a narrow spectral range (determined by the limiting resolution of the system) falls on the detector at any instant of time. In effect, most of the available radiation is thrown away. For example if the monochromator at wavelength λ has mean passband of $\Delta\lambda$ and a scan is being made from λ_1 to λ_2 then at any instant of time, only the fraction $\Delta\lambda/(\lambda_1-\lambda_2)$ of the input radiation is being usefully employed. A great improvement in efficiency can be made by using all of the light for all of the time.

One method of achieving this result is through Fourier Transform Spectroscopy (FTS). White light from the source is launched carefully into the fiber in the usual way but without any wavelength filtering. Thus the full power is transmitted. The output from the fiber is coupled into a scanning interferometer, as shown schematically in Fig. 4, in which one of the mirrors is moved relative to the other. The operation of the interferometer can be understood as follows. For input radiation which is monochromatic the mirror movement causes the total intensity on the detector to vary sinusoidally, with a frequency determined by the mirror velocity and the wavelength of the source. The amplitude of the oscillation is proportional to the light intensity. If there are several spectral wavelengths present in the input signal then each causes a characteristic frequency component to be generated by the detector. The net result is to turn the amplitude/wavelength distribution of the light entering the scanning interferometer into an amplitude/time distribution at the detector output. So by taking the Fourier transform of the detector output the original spectral distribution may be obtained.

The time saved by changing from sequential to simultaneous measurement can be considerable, owing to the large multiplexing factor involved, particularly when a large wavelength range has to be covered with high resolution. As in the cut-back method the loss is obtained by comparing the output from the test length with that from the cut length. A spectral resolution of 10 nm is easily achievable and can be increased, if necessary, simply by increasing the travel on the moving mirror.

Apart from the different signal processing and the essential requirement of a stable light source, the overall system design is unchanged so both multimode fibers (including differential mode attenuation) and monomode fibers can easily be handled.

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The FCm1500 Spectral Attenuation Module

The FCm1500 is the system module which is intended for the measurement of total spectral attentuation. It is suitable for both monomode and multimode fibers. In the case of multimode fibers it may also be configured to measure the differential mode attenuation.

One of the principal aims in designing this attenuation system was to reduce the very long measurement times which are typical with all available commercial systems. Such an improvement has been achieved by utilizing the Fourier transform spectroscopy (FTS) technique.

Launch Optics

Light from a tungsten-halogen source is formed into a beam and launched into the prepared fiber end. The launch conditions are consistent with LPS constraints (Reitz, 1981). The launch spot diameter is automatically controlled at 70% of the core diameter and with a launch NA 70% of the numerical aperture of the fiber. This ensures that the mode distribution of power represents the "steady state" condition of a long length of fiber. In the FCm1000 this condition can be readily specified for both monomode and multimode fibers over the full range of standard diameters. Once specified on the system controller, the correct launch conditions are implemented automatically.

Differential mode measurements are achieved by exciting the fiber with a small diameter beam and scanning this beam automatically in x and y across the fiber face. This ensures that excitation is restricted to a small number of modes. The launch end of the fiber may be placed into a mode stripper if this safeguard is required. The receive end of the fiber is brought up to a cooled detector by means of an easy-to-use specimen holder. Index matching of the fiber to the detector optics is automatic.

Measurement and Signal Processing

The light which is transmitted through the fiber is analyzed in a Fourier Transform Spectrometer (FTS). This approach has been chosen over the traditional scanned monochronometer or serially switched filter methods in order to achieve measurement times which are realistically usable in an industrial environment. The FTS approach is more expensive to engineer and requires computer transformation of the data; however, the system produces a significant multiplex advantage. The end result is that a measurement over the range 600 to 1600 nm (or more) may be achieved in a few minutes (typically less than 5 minutes), whereas the traditional approach will take anything from 45 minutes upwards.

The system is capable of resolution better than 1 nm, although in general one would operate the system with a resolution of 5-10 nm. The signal recovery system which is used in the FCm1500 employs lock-in and multi-point digital signal averaging techniques followed by FFT data reduction. Suitable precautions are taken to remove any effects due to fluctuations in the source intensity.

In defining the operating conditions of this attenuation system, the user may choose either discrete wavelengths or a range of wavelengths. In addition, he can specify the resolution. He may wish to restrict the number of data points and their bandwidth either to reduce the measurement time or to mould the output data to suit his own requirements.

The final data is stored on disk and is available in the form of printer or plotter hard copy. Measurement conditions and sample coding are included in all output modes.

Human Engineering and Economic Considerations

In choosing a given system for measuring the attenuation of multimode or monomode fiber three main variables must be considered:

1) The technical performance specifications
2) The measurement capacity of the system in relation to its capital cost
3) The ergonomics of the system.

Generally, the first point is well recognized and relatively easy to quantify on the basis of the technical specifications provided in data sheets.

The capacity of the system to achieve a number of measurements in, say, an eight hour shift is not often considered. However, a typical conventional system will take 45 to 60 minutes to complete a 100-point scan between 600 and 1600 nm. Its capacity in an uninterrupted eight hour shift would therefore be 8 to 10 fibers. In comparison, the FCm1500 with a five minute throughput time can, in the same eight hour shift, handle 96 fiber measurements of this type. Clearly, with the FCm1000 system, fewer analysis stations are required to handle a given number of fiber measurements. As a result

a) there is a considerable increase in the rapid availability of data – crucial in an industrial environment
b) there is an increase in the number of measurements per test station, reducing the capital cost per measurement and
c) increasing operator efficiency

The third point in evaluating a measurement station concerns the ergonomics or user-friendliness of the system. The FCm1000 is designed to make operation simple and unambiguous. The operator must locate the fiber in a specimen holder which is held in a jig. After placing the specimen holders in the system he must enter a sample code and measurement number. Following this, he is led through the required steps by means of simple choices displayed on the controller display screen.

The operator needs neither to align the specimen nor to alter any parts of the measurement system. All such adjustments are automatically handled by the controller. It is our experience that with this approach to measurement control an operator requires no more than half an hour of instruction before he or she is fully able to get on with the job of characterizing a fiber. The economic implications of such a design are significant. In an industry which is expanding rapidly, the ability to speedily fill new measurement requirements with minimal demands on skill levels provides a major advantage.

Frequently, experienced and skilled personnel are found doing jobs which ought to be routine, but which require their attention because the measurement systems in use are complicated to operate. The possibility of redeployment of such personnel into new opportunities is often very attractive to management and clearly enhances the cost effectiveness of the system.

REFRACTIVE INDEX PROFILING IN OPTICAL FIBERS

The refractive index profile is a very important parameter in the design of optical fibers. It has a critical effect on the bandwidth in multimode fibers and in monomode fibers designed for zero total dispersion. It also affects the cut-off point for single-mode operation in monomode fibers.

Multimode Fibers

In multimode fibers destined for applications requiring a large bandwidth the refractive index profile is normally designed to have a radial variation given by the so-called α-profile,

$$n^2(r) = n_1^2 \left[1 - 2\Delta \left(\frac{r}{a}\right)^{\alpha} \right] \text{in the core}$$

$$n^2(r) = n_1^2 \left[1 - 2\Delta \right] = n_2^2 \text{ in the cladding}$$

where n_1, n_2 are the refractive indices at the center of the core, and in the cladding respectively, $\Delta = (n_1^2 - n_2^2)/2n_2^2$.

r is the radial coordinate

and a is the core radius. Over the region of the cladding immediately adjacent to the core, where the field intensity, although small, is not completely negligible n_2 is assumed to be constant. The exponent α is chosen to minimize the difference in propagation velocities of the large number of propagating modes and is close to 2.0. The precise value depends primarily on the composition of the core.

In most cases the refractive index difference between core and cladding is around 1% so that $\Delta << 1$. The above equations can then be simplified and are usually given as

$$n(r) \simeq n_1 \left[1 - \Delta \left(\frac{r}{a}\right)^{\alpha} \right] \text{in the core}$$

$$n(r) \simeq n_1 \left[1 - \Delta \right] = n_2 \text{ in the cladding} \qquad (1)$$

and in this case $\Delta \simeq (n_1 - n_2)/n_2$.

In principle it should be possible to achieve bandwidth × length products approaching 10 GHz.km in graded-index fibers. In practice the precision required to obtain the optimum profile is beyond the capability of today's fabrication techniques. If the refractive index differs from the ideal value by more than about 0.005 then the bandwidth falls sharply. An error in α of only 0.05, i.e. 3%, increases the intermode dispersion, and therefore reduces the bandwidth, by a factor of 10. A ripple superimposed on the optimum profile with an rms amplitude of 0.6% of the maximum index difference increases the intermode dispersion 40 times. Such errors and distortions can be produced by the layered structure of the deposited materials in MCVD fibers and by the helical striations present in VAD fibers. Consequently any method of determining the refractive-index profile must be capable of high spatial resolution and high resolution (1 part in 10^4) in refractive index.

Monomode Fibers

In monomode fibers the effect of the refractive-index distribution does not influence the bandwidth so markedly, except when the intramode dispersion is close to zero. This means that for operation at wavelengths less than 1 micrometer (i.e. where the main bandwidth limitation is caused by material dispersion) variations in the profile have only a second-order effect provided the range of single-mode operation is not exceeded. However, the situation is very different when attempts are made to maximize the bandwidth between 1.3 μm and 1.6 μm by balancing the contributions of material dispersion and waveguide dispersion. The waveguide dispersion depends very sensitively on core diameter, refractive-index profile and maximum index difference – particularly at the longer wavelengths – so these must all be rigorously controlled.

At all wavelengths the profile affects the energy distribution across the core ("mode profile") and the spot size (i.e. the radius to 1/e of maximum intensity). A difference in spot size between fibers being jointed increases the splicing loss and is to be avoided.

Profiling Methods

It is clear from the above discussion that in order to monitor the bandwidth performance of fibers it is essential to determine the refractive-index profile accurately. Other desirable features in the measuring system, particularly in an industrial environment, are speed, ease of use, low cost, flexibility and minimum sample preparation time. Many profiling methods have been proposed but only those giving the best results or illustrating a principle will be discussed here.

Manufacturers may prefer to obtain the profile of the preform before it is drawn into fiber, for which the fastest and most accurate method is probably transverse scanning in conjunction with spatial filtering. Preform scanning is capable of high spatial resolution but in general the preform is not available and the majority of users require, and prefer, profile measurements on the fiber. Although it is thought that the profile does not change much between the preform and fiber stages, the particular drawing conditions may influence the situation. There could be a change in the shape of the cross-section, particularly when the preform is not perfectly circular, or the core and cladding regions are not accurately concentric.

Classifying Fiber Profiling Methods

Fiber profiling methods can be classified in several ways. Firstly, the fiber can be scanned, or probed, by an external light source in a way that does not make use of any guidance property of the core. The first such technique involved cutting and polishing a thin slice of the fiber and observing interference fringes across a transmitted beam with an interference microscope. It is also possible to observe the reflected power from an incident beam traversed across a perfectly flat end face of the fiber. The variation in reflected power is a measure of the changing refractive index across the surface.

Another series of methods require transverse illumination of the fiber. They are often said to be "non-destructive" but this is not really so because the protective layers must be removed to insert the bare fiber into index-matching liquid, with the consequence that the exposed portion cannot be used again. In any case it is inconvenient, in practice, to cut off a short length.

The transverse illumination takes the form of a collimated light beam which can be made to produce an interference pattern, the details of which enable the core and cladding diameters, as well as the index profile in the core, to be computed. Alternatively the transverse intensity distribution across the beam caused by the fiber acting as a complex cylindrical lens can form the basis of the computation.

Two methods depend on the guidance, or non-guidance, properties of fibers. In near-field scanning the input end of a short length of fiber is fully excited and the near-field intensity distribution at the output is recorded. After corrections have been made for the effect of leaky modes the recorded near-field pattern gives the profile directly. The resolution depends on the number of guided modes so that the method cannot be applied to monomode fibers. In a complementary approach a small spot of light is moved across the input face and the unguided radiation escaping from the side of the fiber is measured as a function of radius. This technique is independent of the number of propagating modes and can be applied under both multimode and monomode conditions.

Finally there are a number of non-optical methods designed to measure the contribution of the glass compounds which are added to SiO_2 in order to modify its refractive index. They include chemical etching, scanning electron microscopy, fluorescence, and X-ray microprobe analysis. None of these has assumed major importance and they will therefore not be discussed in detail.

Accuracy Considerations

Before describing a few of the profiling methods currently in use it may be helpful to outline the nature of the problem. High-quality, low-loss fibers have silica as the main component, with additional oxides such as GeO_2 and P_2O_5 added to raise the refractive index in the core. The cladding is often formed by combining SiO_2 with B_2O_3 or fluorine to lower the index value. Some of the dopants may be present in both core and cladding.

In the MCVD (Modified Chemical Vapour Deposition) or IVPO (Inside Vapour Phase Oxidation) process and also in the OVPO (Outside Vapour Phase Oxidation) process the active material is deposited in the form of layers which may be as thin as 10 μm in the preform and 0.3 μm or less in the fiber. There may be evaporation of dopants from the innermost layer during the preform collapse stage, causing a sharp drop in refractive index in a restricted region at the core center referred to as the "dip" in the profile. In multimode fibers as many as 50-100 layers are contained in a core of 50-60 μm diameter with the dip occupying 1 or 2 μm or less. The index difference between the cladding and the maximum in the core is about 0.02 in 1.5, or just over 1%.

The core of a monomode fiber comprises only 1 or 2 layers over a diameter of 4-8 μm while the deposited cladding extends to perhaps 50 μm. The refractive index difference is somewhat smaller than with multimode fibers, in the region 0.005-0.01. Ideally a spatial resolution in measurement of about 0.2 μm is desirable, in addition to the accuracy in n, mentioned in the introduction, of 1 in 10^4.

Fibers made by the VAD (Vapour Axial Deposition) process, whereby a soot preform is rotated slowly and withdrawn as further soot is deposited on the end from an oxidizing burner, have no layers. The spiral structure present in the collapsed preform is presumably present with a long pitch in the fiber, but it is not usually resolved.

In fibers intended for communication purposes the aim is to have good circularity and concentricity of core and cladding within the substrate region. In practice some non-circularity may be introduced during the preform collapse stage and may affect adversely the profile measurement. Fibers intended for some sensor applications are made highly birefringent by deliberately causing the core to become elliptical. Not all of the profiling methods are applicable in this case.

Interferometry on Thin Slices

In the early days of fiber technology, thin-slice interferometry was the only technique available for profiling. A section of fiber (10-50 μm thick) is cut and polished to make the faces optically flat and parallel. The fiber slice is then placed in one side of an interference microscope with a homogeneous reference slab in the other. In the transmission method, light from a suitable source is split into two components, each of which passes through one of the slices, before being recombined and viewed through the microscope objective. If the slices are identical blanks and the two beams are tilted slightly with respect to each other, then a series of linear fringes is formed with a spacing that depends on the angle of tilt. If one of the blanks is replaced by the fiber slice then the changed optical path length in the region of the core causes the position of the fringes to move relative to those in the cladding, as shown in Fig. 1. The fringe

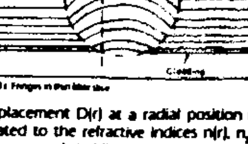

Fig.1: Fringes in thin fiber slice

displacement D(r) at a radial position r is related to the refractive indices n(r), n_2 in the core and cladding respectively, by

$$n(r) - n_2 = \frac{\lambda D(r)}{td} \quad (2)$$

where λ = wavelength of observation
t = thickness of slice
d = fringe spacing in the cladding

In the equivalent reflection method the fiber sample is placed on a reflecting surface in one arm of a Michelson interferometer (thus doubling the effective thickness of the sample) and the other arm contains a plane mirror.

Visual observation can give only a qualitative assessment, so that it is best to couple a vidicon camera to the microscope and digitize the output. For checking purposes the fringe pattern may be displayed on the monitor. To obtain quantitative results the digitizer is coupled to a computer for automatic control and processing of the data. A sampling line (shown dashed in Fig. 1) scans across the fringe pattern, accurately locating the intensity minima in cladding and core regions and recording the fringe displacement. The profile is then computed from Equation (2) and displayed on the monitor or plotted on a chart.

The thin-slice interferometry method can, with care, be made accurate but it is limited in spatial resolution. It is also very costly, both in terms of equipment (the interference microscope in particular) and the manpower required for cutting, polishing and monitoring of slice preparation. A measurement on a single fiber could take a whole day.

Not only is sample preparation difficult, it is also time-consuming. The slab must be sufficiently thin that the light is not noticeably deflected in traversing it; in addition the regions of different composition may polish at different rates, and the resulting thickness variations can cause serious errors. The apparent inherent accuracy of the method is therefore difficult to achieve in practice.

Reflection Method

The fraction R of light reflected from a glass surface depends on its refractive index and for normal incidence is given by

$$R = \left(\frac{n-1}{n+1}\right)^2 \quad (3)$$

Equation (3) suggests a method of profile measurement that is potentially simple and non-destructive, requiring access to only the end face of a fiber. A suitable technique would be to scan a small laser spot across the core region and measure the variation in reflected power. Alternatively the end-face could be illuminated and viewed through a microscope objective, and the localized reflection monitored by a scanning photodiode or by an electronically-scanned photodiode array.

It must be recalled, however, that the total variation of n is only about 1% and it has to be determined with an accuracy of 1 in 10^4 or better. This is not possible with any existing reflection method. Furthermore the refractive index measured is that of the end-face, and it is well known that glass surfaces quickly tarnish by the absorption of impurities (water vapour in particular) from the air. Polishing also changes the character of the surface layers and should be avoided. Because of these difficulties, and the poor resolution obtained, the reflection method will not be considered further.

Transverse Interferometry

In transverse interferometry a bare fiber is viewed transversely in an interference microscope. The reference arm of the microscope contains index-matching oil of the same refractive index as the cladding, and the fiber is immersed in index-matching oil to prevent changes of ray angle, and reflection, that would otherwise be caused by the outer cladding boundary.

Each light ray traversing the sample passes through regions of varying refractive index so that the total optical path length must be expressed as an integral. A series of displaced fringes is observed, as in the slice method, and the refractive index n(r) is obtained from the fringe displacement D(ε) as follows:

$$n(r) - n_2 = \frac{\lambda}{\pi d}\int_r^{\infty}\frac{dD(\epsilon)}{d\epsilon}\,(\epsilon^2 - r^2)^{-1/2}\,d\epsilon \quad (4)$$

where ε is the offset of the ray from the center.

Fringe analysis and computation can again be carried out with a vidicon camera, digitizer and microcomputer.

The transverse interferometric method can resolve large refractive-index fluctuations in localized regions. However, it relies on circular symmetry of the fiber and the accuracy is 10 times smaller than with slice interferometry. In particular it is unreliable in the region near the fiber axis.

Transverse Convergence or Focusing

In another method involving transverse illumination, a collimated light beam of uniform intensity over its cross-section is passed through the fiber in the direction normal to the fiber axis and each constituent ray traversing the core is deflected (see Fig. 2). As in the preceeding method,

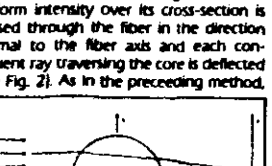
Fig.2: Deflection of ray passing transversely through core

the fiber is placed in index-matching liquid to nullify the effect of the cladding surface. Thus rays passing through the center of the core or just grazing its edge are undeflected, while intermediate rays change direction by an amount depending on their position.

At a suitable observation plane the non-uniform light intensity distribution in the y direction (which is a function of the refractive-index profile in the fiber) is viewed through a microscope and recorded by a video camera. The observation plane is determined by the object plane on which the microscope and camera are focused. It must not be inside the core, nor so far from the core that ray cross-over is allowed to occur. The necessary digitization of data, calculation, and display is controlled by a computer.

Provided the core is circularly symmetric the focusing method gives an accuracy and resolution similar to that obtained using slice interferometry. Disadvantages arise from the need to measure light intensities accurately. The optical components, matching oil and fiber should therefore be very clean; the video camera must be linear in response and have a uniform spatial sensitivity across the detector area in use. The error is largest at the core center, as with transverse interferometry. Owing to its limited spatial resolution, the transverse convergence method is more advantageously applied to preforms than to fibers.

Near-Field Scanning

The origin of the near-field scanning method lay in the observation that when light is launched into a short length of fiber, the intensity at a point on the output end-face seems to correlate with the refractive index at that point.

The method is therefore conceptually very simple. A short length of fiber (10-20 cm) is uniformly illuminated by a Lambertian source (usually a high intensity arc lamp or LED) so that all modes are equally excited. For a straight, unstressed fiber in which there is neither mode coupling nor differential mode attenuation, the intensity I(r) at any radial point in the output near field is proportional to the refractive index n(r), provided there are no leaky modes. Thus

$$\frac{I(r)}{I(0)} = \frac{n^2(r) - n_2^2}{n^2(0) - n_2^2} \simeq \frac{2n_2\left[n(r) - n_2\right]}{\left[N(0)\right]^2} \quad (5)$$

where N(0) is the numerical aperture at r = 0.

To measure the near-field intensity one can either form a magnified image of the output end of the fiber and scan a small detector across the image plane, or a small spot of light (of numerical aperture exceeding that of the fiber) may be traversed across the input end and the total light output collected. In either case the refractive-index profile is plotted out directly.

However, a difficulty arises because the fiber contains leaky modes which are not properly guided but "leak" away at a rate depending on the mode parameter. Some leaky modes are quickly lost but others may persist for a considerable distance and contribute to the output power from a short length. A "leaky-mode" correction must therefore be made to the observed near-field intensity distribution.

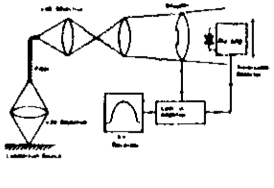
Fig.3: Near-field scanning of multimode fiber

Another problem is that the finite number of guided modes in a practical fiber, each with its own power distribution, gives rise to a ripple in the near-field pattern. The period of this ripple is proportional to V^{-1} where V is the normalized frequency $(2\pi a/\lambda)(n_1^2 - n_2^2)^{1/2}$. The ripple amplitude is small at large V, so the effect can be reduced by operating at shorter wavelengths, as well as by increasing the line-width of the source to 100 nm.

The near-field method is simple and produces results rapidly, with the minimum of sample preparation. With careful experimental technique the corrected near-field scans give accurate profiles, although some laboratories report better results for near-square-law fibers without applying a correction for leaky modes.

Refracted Near Field Technique

The refracted near field technique is the complement of near-field scanning. The latter uses the fact that the near-field intensity distribution of the bound modes is proportional to the refractive-index profile. The additional presence of leaky modes, which cannot be distinguished from bound modes, complicates the situation. An alternative method is to measure the intensity of the refracted modes that are lost sideways from the fiber. Leaky modes are also radiated but they can easily be blocked by a suitably shaped screen so that only refracted modes reach the detector. The refracted light intensity is directly related to the index profile.

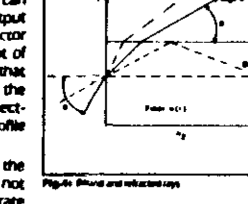
Fig.4: Bound and refracted rays

The method is illustrated in Fig. 4. A small spot of light, having a convergence angle exceeding the maximum numerical aperture of the fiber, is focused on the end face. The fiber is immersed in index-matching liquid having the same refractive index as that of the cladding, so that rays leaving the core and striking the outer cladding surface can escape. Part of the input radiation (illustrated by the dotted line representing a ray at a moderate angle) is guided by the core and transmitted to the output end. Since the input beam is made to overfill the numerical aperture, rays at large angles (such as the solid line representing the extreme ray) are refracted out of the core. If the numerical aperture of the fiber is reduced, for example by moving the spot across the end face, then the angle Ø made by the refracted ray with the axis is increased (as shown by the dashed line) and conversely. The angle Ø is related to the

local numerical aperture of the fibe
and the angle θ of the input ray to th
by

$$n^2(r) - n_2^2 = \sin^2\theta - \sin^2\emptyset$$
where $N(r) = \left[n^2(r) - n_2^2\right]$

and n_2 is the refractive index of the cla
which is assumed to be constan
amount of refracted light leaving the
thus a measure of the refractive inde

It would be a simple matter to focu
the radiated light onto a detector bu
modes appear along with the ref
modes in the solid cone of light leavi
fiber. The great virtue of the refract
technique arises from the fact that the
modes (rays) leaving the core eme
small angles. They can therefore be
pletely blocked by placing behind th
(see Fig. 4) a circular disc, or stop, of a
priate diameter (or more precisely
tending a suitable angle $\emptyset_s$ at the
end). Although not all of the ref
radiation now reaches the detector,
not important. With a Lambertian s
the power P(r) transmitted past the s
given by

$$n^2(r) - n_2^2 = 2n_2\,\Delta n(r)$$
$$= (\sin^2\theta - \sin^2\emptyset_s)\,[P(r)/P$$

where r is the radial position of the
spot and P_2 is the power received wh
fiber is replaced by index-matching o
practice) the input spot is moved out
cladding. Thus the power trans
beyond the stop is proportional t
refractive index at the input surface

A schematic diagram of a typical e
mental arrangement is given in Fig.5
from a low-power laser is first expanc
provide an approximately uniform dis
tion across an aperture and is then fo
by a microscope objective onto the
end-face of the fiber. A quarter-wave
is inserted to change from linear to ci
polarisation, since the reflectivity of lin
polarised light at an air/glass interf
strongly dependent on the incident
and the input beam may have a cc
gence angle of 30° or more. The fiber i
in the measuring cell by a capillary tub
the output end is taken off at right an
the direction of scan and inserted
index-matching oil to ensure tha
radiation is reflected back to the inpu
hollow cone of refracted rays is collec
a condensing lens system (not shown i
5) and directed to a large-area det

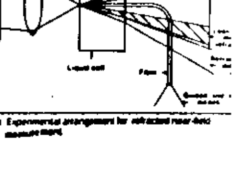
Fig.5: Experimental arrangement for refracted near-field measurement

Arrangements must also be made for viewing and aligning the fiber and for focusing the input beam accurately on its end surface.

Most of the adjustments necessary during setting up of the equipment are straightforward. The critical one is to ensure that the axis of the incident cone is parallel to the axis of the fiber, to better than 0.3°, otherwise the scans are skewed slightly from one side to the other. This asymmetry can be used to monitor misalignment of the two axes. A three-axis manipulator with a precision of 0.5 μm or better is required, with a precision motor drive in the scanning direction. The entry face of the fiber must be normal to the axis to within the depth of field, say 2-4 μm, (corresponding to an end-face angle of 2-4°). For maximum resolution the convergence angle of the incident cone should greatly exceed the numerical aperture of the fiber.

Both monomode and multimode fibers can be easily handled. Perfect step-index distributions present a problem since the circular stop does not then block the extremely leaky modes. It does, however completely block leaky modes at all core radii up to a value given by

$$\frac{r}{a} = \left[1 - (N_f/N_l)^2\right]^{1/2}$$

where N_f, N_l are the respective numerical apertures of the fiber and the focusing lens. In practice $r/a > 0.9$ but even outside this radius the majority of the leaky modes are still rejected, so this limitation is not a serious one.

By appropriate design of the optical system a spatial resolution limit of 0.35 μm has been achieved. This is more than adequate for the majority of fibers. For a fiber numerical aperture of 0.2 the profile of the core relative to the cladding can be obtained to an accuracy of +/− 0.00015. These results indicate that the refracted near-field technique has an accuracy and resolution that cannot be bettered by any other method. It also has the advantages that it does not require an interference microscope, nor elaborate computer processing of the data; it is non-destructive, requires little fiber preparation and it gives a complete scan in only 2-3 minutes. As demonstrated by the profile in Fig. 6, the central dip can be satisfactorily resolved as well as sharp depressions at the core boundary.

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The FCm1400 Refractive Index Profiler

The York Technology Refractive Index Profiler is an engineering development of the Stewart and Stewart/White system (ref W.J. Stewart, IOOC Tokyo, 1977).

The unit has been under continuous development for the past three years and has undergone extensive evaluation in research applications and in industrial environments. It is equally applicable to monomode and multimode fibers.

Launch Optics

The FCm1400 profiler is an ultra-high resolution model based on the refracted near-field technique. A 633 nm laser beam is focused into a very small spot by an immersion objective of numerical aperture, NA = 1. The spot is then scanned across the fiber end-face by a precision x-y scan table.

Some of the light which impinges on the fiber face will satisfy guidance constraints and will therefore propagate along the fiber core; the rest of the light will fail to satisfy such constraints and will be refracted out of the fiber. For a given excitation level, the amount of light which leaves the fiber is dependent only upon the refractive index at the point of entry.

Signal Detection and Processing

As the spot is moved across the fiber end face it meets a changing local refractive index. The amount of light leaving the fiber will therefore vary as the spot is scanned across the end face. A patented light collection system is employed to ensure that all this refracted light is measured at the detector. The signal at the detector will therefore vary directly with change in refractive index and a profile of the fiber is obtained.

While the principle of this system is relatively simple, the optimum implementation requires very high quality beam optics and demands precision x-y and z control of the fiber end-face. Such accurate position and velocity control are only achievable with feedback elements which have a resolution in the nanometer range.

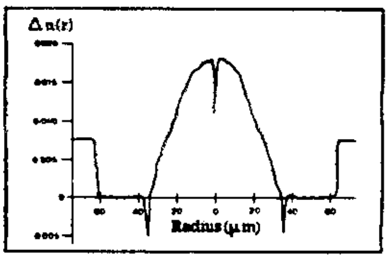

Fig.6: Refracted near-field profile of multimode fiber

The signal output of the detector is digitized, averaged and analyzed to provide the index profile for the user. This information is also used by the automatic control system to position the fiber with respect to the exciting beam, and it can, in addition, be used to give automatic beam focusing. Operation in this mode removes subjective operator judgements from the measurement.

The FCm1400 not only provides an instant refractive index profile of the entire end face of the optical fiber; it also gives the basic data set for further analysis by the controller. Such analysis yields core and cladding diameters, concentricity of core and cladding, and departures from circularity. It must be emphasized that the International Standards committees in both Europe and the USA recommend that such dimensional data be based on refractive index data. The automatic location and focus information is used to great effect in setting the conditions of measurement of the other FCm1000 modules such as attenuation, backscatter etc.

All basic data and computed data is stored on disk and may be preserved in printer or plotter hardcopy.

Human Engineering and Economic Considerations

A great deal of engineering attention has gone into producing a fiber characterization system suitable for use in an industrial environment. While the actual measurement techniques of the FCm1400 represent the state of the art, the operation of this system does not require specialist attention. Typically, one hour spent in familiarization is sufficient preparation.

After the specimen is loaded, the operator can check the end face quality (option m1300). If the fiber is judged to be of acceptable quality for measurement, the operator is then asked to specify the fiber code and a measurement number.

Definition of measurement conditions can be preset, or the operator may change the conditions by following the simple menu which is presented on the controller screen. All physical adjustments in the system are carried out by the system controller. The time savings effected by this automatic alignment, measurement and analysis represent a considerable cost saving.

DISPERSION AND BANDWIDTH

The maximum distance over which signal transmission is possible using optical fibers is limited by both attenuation and dispersion. Current manufacturing techniques enable very low levels of attenuation to be obtained, making the limitations imposed on the bandwidth by dispersive mechanisms of increasing importance.

When dispersive effects are present the different frequency components of a signal travel at different velocities. The result is distortion of an analog signal or the spreading out (in both space and time) of digital pulses. In the absence of attenuation the total energy in a pulse remains constant, so there is also a loss of signal amplitude as the pulse broadens. Dispersion eventually causes the output pulses to overlap, producing errors in the detected pulse train. It consequently sets limits on the propagation distance and the maximum pulse rate.

Dispersive Mechanisms

There are two general types of dispersion: (a) intermode dispersion, which occurs only in multimode fibers, and (b) intramode dispersion. The latter results from material effects and waveguide effects, and applies to both types of fiber.

Intermode Dispersion

In a multimode fiber intermode dispersion is usually the dominant process. It arises because the various groups of modes have different propagation velocities, causing the many mode components excited by an input pulse to arrive at the output over a longer time interval, and the emerging pulse is broadened as described above. The need to avoid overlapping of the output pulses sets a limit on the maximum pulse rate – about 20 Mbits/s over 1 km in step-index fibers. By introducing the appropriate radial variation of refractive index, the spread of group velocities between the various modes can be greatly reduced. It is then possible to achieve pulse rates of 1 Gbit/s over 1 km and in principle much higher values would be attained if the refractive-index profile could be controlled sufficiently accurately.

Intramode Dispersion

If pulse rates greater than 1 Gbit/s are required then it is necessary to resort to single-mode operation. In theory, large-core fibers could still be used if a single mode were launched, but in practice bends and other inhomogeneities cause mode conversion. The number of modes increases in a random uncontrolled way, giving rise once again to multimode effects. To ensure that only the fundamental mode can propagate the core diameter is reduced to 5-10 μm. Intramode (chromatic) dispersion, with its waveguide and material components, then becomes the limiting mechanism.

Waveguide dispersion arises because the group velocity in almost any waveguide (even one of 'dispersionless' materials), changes with wavelength. The different spectral components therefore have different propagation times.

Material dispersion is an inherent property of glass materials and arises from the spectral dependence of refractive index $n(\lambda)$. The group velocity thus varies with wavelength so that even in the bulk material a pulse broadens as it propagates. The amount a pulse spreads in travelling a distance L is given by

$$\Delta t = L\, M(\lambda)\, \Delta\lambda$$

where $\Delta\lambda$ is the signal bandwidth and $M(\lambda)$ is the material dispersion parameter of the core, given by

$$M(\lambda) = \frac{\lambda}{c} \frac{d^2 n(\lambda)}{d\lambda^2}$$

$M(\lambda)$ is normally expressed in the units ps/nm km and is about 100 ps/nm km at 0.85 μm falling to zero at 1.3 μm. Fig.1 shows the wavelength dependence of the material dispersion parameter in a germanosilicate fiber.

One of the attractions of multimode fibers is that a light-emitting diode (LED) can act as a simple, relatively cheap, source capable of modulation at up to several hundred megabits/second. However, the spectral linewidth is 20-40 nm, so that at a wavelength of 0.8 - 0.9 μm the pulse broadening in an individual mode caused by material dispersion (40 nm × 100 = 4000 ps/km) becomes comparable with the intermode dispersion. This limits the maximum bit rate, to about 200 Mbits/s over 1 km in graded-index fibers. At longer wavelengths material dispersion is less important and intermode dispersion again predominates.

The relative effects of intermode and material dispersions with semiconductor laser and LED sources are shown in Fig.2. It can be seen that a change of LED operating wavelength from 0.85 μm to 1.3 μm produces a dramatic increase in bandwidth, which then becomes comparable with that attained using a laser.

A laser source is necessary with monomode fibers because the LED launching efficiency is so small (except perhaps with edge-emitting devices). The linewidth of most existing semiconductor lasers is about 2 nm *giving a material dispersion component of*

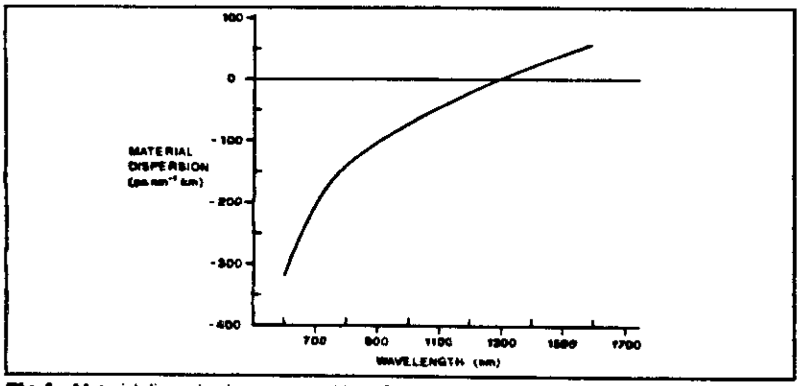

Fig.1: Material dispersion in a germanosilicate fiber.

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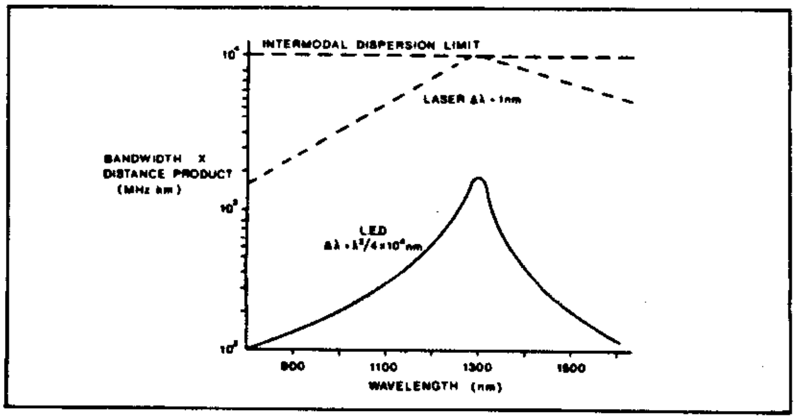

Fig.2: Bandwidth limitation resulting from material dispersion in a typical $GeO_2 - P_2O_5 - SiO_2$ multimode fiber.

approximately 0.2 ns/km at wavelength 0.85 μm. Recent improvements in device technology may enable this figure to be reduced considerably.

At wavelengths beyond 1.3 μm material dispersion and waveguide dispersion in monomode fibers can be made to mutually cancel each other, giving zero total intramodal dispersion. The next limiting factor then becomes the difference in propagation velocities of the two orthogonal components of the fundamental (HE_{11} or LP_{01}) waveguide mode. Under these conditions an intramode dispersion of less than 1 ps/km has been observed, but such measurements require very long lengths of fiber and specialized equipment.

Measurement of Pulse Dispersion

To determine the pulse dispersion of a fiber experimentally, a short optical pulse is launched into the fiber and the pulse widths at output and input are compared. It can be shown from convolution theory that if the r.m.s. widths of the input and output pulses are σ_i and σ_o then the r.m.s. width of the impulse response function is given by

$$\sigma_h^2 = \sigma_o^2 - \sigma_i^2$$

where σ_h is the impulse response of the fiber. Having obtained σ_h from one measurement of σ_i and σ_o, it can then be used to calculate the pulse dispersion and the maximum permissible bit rate for any width of input pulse.

In a typical pulse dispersion measurement a semiconductor laser is triggered repetitively by a high-speed pulse generator and emits short pulses of sub-nanosecond duration. A beam-splitter at the fiber input enables the launched pulse to be displayed and its width measured. As with loss measurements, the launch conditions must be carefully controlled. The beam position and angle of entry must be chosen either (a) to give maximum launching efficiency into the fundamental mode, for a monomode fiber, or (b) to represent the equilibrium mode distribution for multimode fibers – by using the limited beam optics (limited phase space) launch condition, for example.

The fiber must be properly supported to minimize strain and microbending which cause mode conversion effects that may not be typical of those present in the final installation. Fast, low-noise, avalanche or PIN detectors are essential, and the output (and input) pulses can be displayed on a sampling oscilloscope or (preferably) taken to a standard digital programmable oscilloscope. The appropriate signal averaging, processing and deconvolution is then carried out.

The impulse response of a fiber may not have a linear length dependence, so care must be taken in applying the results of pulse dispersion measurements to system design. Like its transmission loss, the impulse response of a fiber depends upon (i) the input mode distribution, (ii) mode coupling and (iii) differential mode attenuation. Coupling introduces an energy exchange between the modes and reduces the spread in propagation times when many modes are present. If mode coupling is complete then theoretically the dispersion would increase as the square root of length L. With no mode coupling there is a linear length dependence. Modern fiber fabrication techniques give only a small amount of mode coupling; however after cabling and installation the length dependence is generally L^n where n is in the range 0.8 to 1.0. Differential mode attenuation reduces the number of modes and therefore the dispersion.

Differential Mode Delay

The radial variation of refractive index introduced into graded-index fibers is intended to equalize, as far as possible, the group velocities of all the modes. Consequently, departures from the ideal refractive-index distribution can be detected by measuring the propagation times of restricted groups of similar modes, and observing the difference in group velocities directly. A simple method of exciting the desired number of modes is to launch an accurately controlled small spot of light which can be moved across the end face. When the spot is at the center of the core the modes induced are of low order. As the launch point is moved outwards to the core/cladding boundary the modes change progressively to higher-order ones.

A differential mode delay (DMD) measurement therefore involves launching a short pulse of light into a fiber through a small spot that is traversed across a radius of the core, and recording at the output the variation in delay time of the transmitted pulse. The optimum width w of the incident beam for DMD measurements is given by

$$w = \left(\frac{\lambda a}{n_1 \pi}\right)^{1/2} (2\Delta)^{-1/4}$$

where a is the core radius, $\Delta = (n_1 - n_2)/n_1$ is the relative index difference and n_1, n_2 are the maximum refractive index at the core centre and in the cladding, respectively. By launching the beam parallel to the axis and at a distance r from it the modes will all be of compound mode number m, where in a near-parabolic fiber

$$\frac{m}{m_m} = \left(\frac{r}{a}\right)^2$$

and m_m is the largest possible value of m for guided modes in the fiber being tested.

Assessment of the differential mode delay is a much more sensitive indicator of departures from the optimum refractive index distribution than is measurement of the profile directly. Hence it is very useful in monitoring the performance of multimode fibers.

The ideal refractive-index distribution n(r) is normally taken to be the α-profile, defined as

$$n^2(r) = n_1^2 [1 - 2\Delta (r/a)^\alpha]$$

where the optimum value of the numerical exponent α depends on the materials and the wavelength but is close to α = 2. Fig.3 illustrates the situation in a fiber for which the optimum is exactly 2.0. It shows that the DMD is constant over all modes and the bandwidth should theoretically be 20 GHz km.

If the value of α in the test fiber is below optimum then the high-order modes arrive before the low-order ones. When α is too large the low-order modes arrive first. Quite small departures from the optimum α lead to large differential mode delays. Thus if α changes by 10% to 2.2 (owing to manufacturing imperfections, for example) then the bandwidth falls to 0.3 GHz km. The change in mode delay between the centre and the edge of the core is therefore 2 ns/km and is well within the range of practical measurement, even though the maximum error in refractive index (only 0.0026) is very difficult to detect.

Furthermore, DMD measurements give an indication of the location of the error in the profile, with respect to the fiber axis. This can be deduced from the way in which the delay varies with mode number – for example in Fig.3 the dotted lines refer to a fiber where the profile is optimum from r = 0 to r = 0.7a but then becomes α = 2.2 over the range 0.7a < r < a. The change in refractive-index profile is barely discernible, whereas the position and magnitude of the altered DMD is very clear.

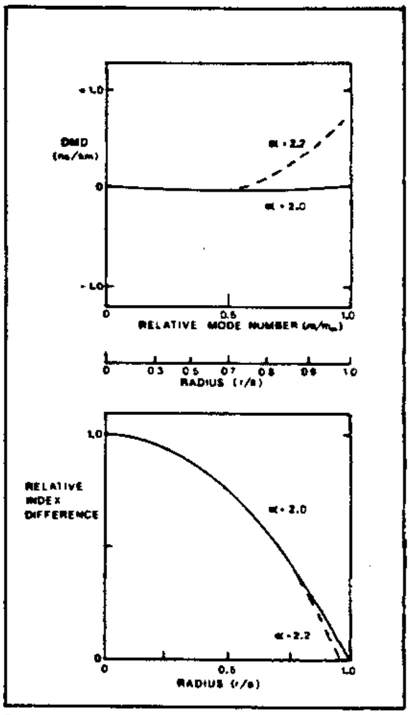

Fig.3:
Effect of a small departure from the optimum refractive-index profile on the differential mode delay. The curves for $\alpha = 2.2$ assume that the profile changes from optimum (in this case $\alpha = 2.0$) at $r > 0.7a$.

When performing DMD tests the beam-forming optics and the spot size must be very accurately controlled. It is also advisable to assess whether any appreciable degree of mode coupling is present, for if power is coupled to other mode groups then DMD measurements become impossible. Fully coupled modes give zero differential mode delay even for a poor profile. A simple check can easily be made since strong mode coupling produces an output radiation pattern that is nearly independent of the launching conditions. In most fibers the optimum refractive-index profile can be achieved at only a single wavelength and for the best results the DMD measurement must be made at the same wavelength.

A typical illustration of the use of DMD characterization is in a fiber production plant where a particular lathe station is producing fibers that show up poorly on a quality assurance test of total pulse dispersion or bandwidth. A DMD characterization indicates immediately whether it is the profile at fault.

Bandwidth

If the impulse response of a fiber has been determined by a pulse (time domain) measurement of the type described above then the frequency response is easily obtained by standard Fourier transform techniques. In fact this is the most appealing method when the fiber is to be used in a digitally-modulated system, where knowledge of the pulse performance is more useful. Frequency-domain measurements require a signal generator which is tunable from a low frequency up to the gigahertz region and is capable of driving suitably a semiconductor laser, LED or external modulator. The same launching conditions apply as in pulse measurements. Either modulated semiconductor lasers or LEDs are suitable, and for both sources there is excellent agreement between the frequency-domain and the time-domain measurements on a fiber, provided the launching conditions are the same.

In principle it should be possible to calculate the impulse response and the frequency response from the refractive-index profile. In practice the calculation is very difficult and time-consuming since it is necessary to measure, and include, the profile dispersion in the computation. The particular launch distribution must be known, together with the amount of mode mixing and the differential mode attenuation. A further problem is that the profile may vary along the length of the fiber. These factors make it difficult for calculation to reach agreement with the measured value, even as close as a factor of two. The measurement of pulse dispersion, however, is fast and accurate and has the additional advantage that the fiber is being assessed more nearly for the conditions under which it will operate.

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OPTICAL TIME-DOMAIN REFLECTOMETRY (BACKSCATTER MEASUREMENTS)

Backscatter measurements in optical fibers are used to locate breaks, faults and poorly-made joints, and to identify other inhomogeneities which have characteristic backscatter returns, such as diameter fluctuations and bubbles. They can also reveal the variation of local attenuation along the length of a fiber, so that a complete signature of an optical communications link can be obtained.

Principle of Operation

Optical fibers contain irregularities that are introduced during the fabrication process. Some of these are unavoidable, such as the microscopic density fluctuations frozen into the core and cladding glass when they are cooled from the liquid state into a solid. The variations in density produce a corresponding random structure of refractive index about its mean value, thus causing a small but significant degree of scattering of any light passing through the medium. The regions of density, and refractive index, fluctuations are much smaller than 1 μm in extent, so that the amount of power scattered changes with wavelength as λ^{-4} in accordance with the well-known Rayleigh law. "Waveguide scattering" may also occur, caused by irregularities in the core/cladding boundary. This type of scattering is, in principle, avoidable and may be reduced to a low level by taking suitable care during the fiber drawing stage.

Whereas Rayleigh scattered light is emitted at all angles, waveguide imperfections tend to scatter light preferentially in the forward and backward directions. Some of the backscattered radiation is guided by the fiber back to the launching end and may be detected by suitable techniques.

When an optical pulse of duration Δt is launched into the fiber, its energy is distributed over a length $\Delta L = v_g \Delta t$ where v_g is the propagation velocity. The power returned to the input end can be coupled out to a detector using a beam-splitter. By gating the receiver circuit to observe the reflected power at a time t after the input pulse, the observed signal will be characteristic of a point along the fiber which is at a distance $L = (½)tv_g$ from the source. Both the input pulse and the backscattered power are attenuated by the length L of fiber between the scattering point and the source; hence the return signal from a uniform fiber will decay exponentially with time. The reflection from a poorly-made joint will show up as a spike on this curve and the time delay t of the signal return indicates the position of the joint with a resolution of ΔL. The system is, in effect, an optical radar.

Fault Location

Since fault location is the simplest application of the backscatter technique it will be described first.

A schematic arrangement of the components is shown in Fig.1. A laser injects short pulses into the test fiber through a beam-splitter and suitable launching optics. The fiber is immersed in index-matching liquid to reduce the large reflection from the input end; even so there is usually sufficient reflected light to provide a monitoring signal for timing. The effect of the input reflection can also be reduced by gating the detector or, alternatively, by launching polarized light and inserting a crossed polarizer into the detector beam (since the scattered light is unpolarized). The problem with the latter arrangement is that it reduces the amplitude of the signal at the detector.

For field use an injection laser is a convenient light source since it is small, efficient and easily modulated, and in fault location the wavelength is not critical.

The reflected signal from a break, bad joint or other fault is large compared with scattering and appears after time t as a distinct peak on the return signal, illustrated in Fig.2. As shown above, the location of the fault is at distance $½v_g t$ from the input. The group velocity v_g is intermediate between that of pulses in the bulk core, and bulk cladding, materials and since the relative index difference is small, usually ~1%, we can put $v = c/n_1$ where n_1 is the maximum refractive index in the core. The fault is then at a distance $c\,t/2n_1$ from the input end and can be located with a resolution of

$$v_g \Delta t/2 = c\Delta t/2n_1.$$

Loss Measurement by Backscattering

Whereas the cut-back method of measuring fiber attenuation is very accurate, can be applied to long lengths, and is capable of high spectral resolution, its disadvantages are that both ends must be accessible (although not necessarily in the same location), the attenuation obtained is the average over the entire length of the fiber, and a few meters of fiber are lost during each test.

The backscatter method requires access to only one end of the fiber, it is not destructive, and it can give information about inhomogeneities and loss at any point along

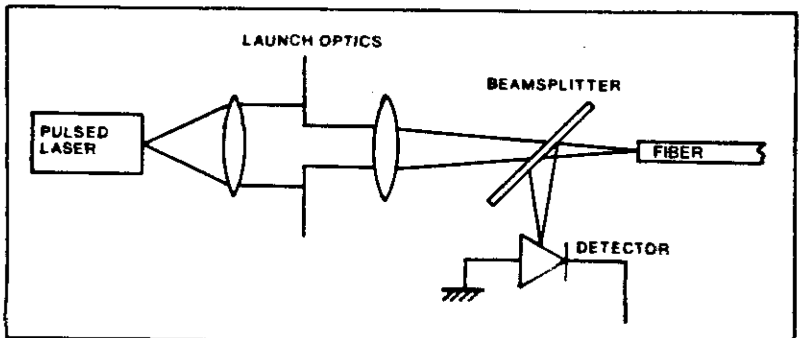


Fig.1: *Simple backscatter method.*

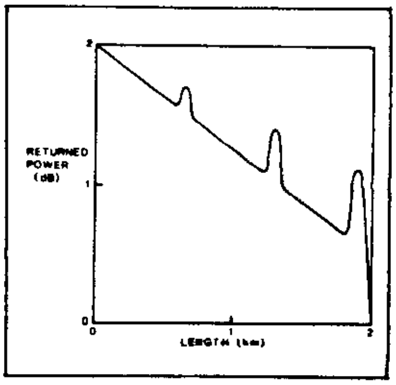


Fig.2: Backscatter signal from jointed length of fiber.

the fiber. However it requires a source of very short pulses, and spectral measurements are much more difficult and costly because tunable pulsed sources are inconvenient and expensive. The technique thus forms a very useful complement to the cut-back method, but does not replace it.

The optical pulse launched into a fiber suffers attenuation at a rate of a_f as it propagates in the forward direction and the backscattered signal sees a similar attentuation loss a_b. If the scatter rate is constant along the fiber then the returned signal decreases in intensity at a rate $(a_f + a_b)$dB/km, and the value of $(a_f + a_b)$ is given by the slope of the curve in Fig.2. In a monomode fiber $a_f = a_b$ and there is no problem. But in multimode fibers, the backscattered radiation usually has a different mode distribution from the forward-propagating signal. This follows because high-order modes are preferentially reduced through differential mode attenuation, thus producing a changing mode distribution. Hence in a multimode fiber a_f will probably differ somewhat from a_b, although the difference is generally small. The backscatter method measures the average of a_f and a_b.

Single-Channel Method

In the single-channel method the fiber attenuation is obtained simply by taking the slope of the curve in Fig.2. Because the intensity of the scatter signal is small, suitable techniques are necessary to reduce the effect of detector noise. Integration of the detector output enables the signal amplitude to build up coherently while the superimposed random noise elements tend to cancel each other. One method is to feed the output into a boxcar integrator followed by a logarithmic amplifier and X-Y recorder for display. For single-channel measurement it is essential that the optical source and the detector are very stable in operation, since any variation in signal level during averaging limits the accuracy of the measurement. Hence injection lasers normally need to be temperature stabilized.

The accuracy of the single-channel method is limited because of the need to measure the slope of an experimental curve.

Two-Channel Loss Measurement

A development of the backscatter technique is available which avoids many of the difficulties encountered in single-channel signal processing. Stability problems are overcome by taking samples of the backscattered signal at two different times after the pulse is launched, and the attenuation is derived directly from the ratio of the samples. Numerical averaging is carried out by a microprocessor rather than an expensive and bulky boxcar integrator.

A suitable arrangement is given in Fig.3. An optical pulse is launched into the fiber and the resulting backscattered power is monitored by an avalanche photodiode and amplified for analysis. A time-delay generator causes the sample-and-hold circuits SH1 and SH2 to record the amplified backscatter signal at times t_1 and t_2 respectively, a small fraction of the input pulse being reflected from the beam-splitter to provide a timing reference. Because the time-delay generator is synchronized by the input pulse to the fiber, any time jitter in the laser output does not result in uncertainty in the time position of the sampling windows. The analogue samples $p(t_1)$ and $p(t_2)$ are converted into digital form for processing and many such samples can be averaged to give the mean attenuation $\hat{a}(t_1,t_2)$ over the length of fiber l_{12}, where

$$\hat{a}(t_1,t_2) = \frac{\ln[\hat{p}(t_1)/\hat{p}(t_2)]}{v_g(t_2 - t_1)}$$

and $t_1 v_g < 2l_{12} < t_2 t_g$.

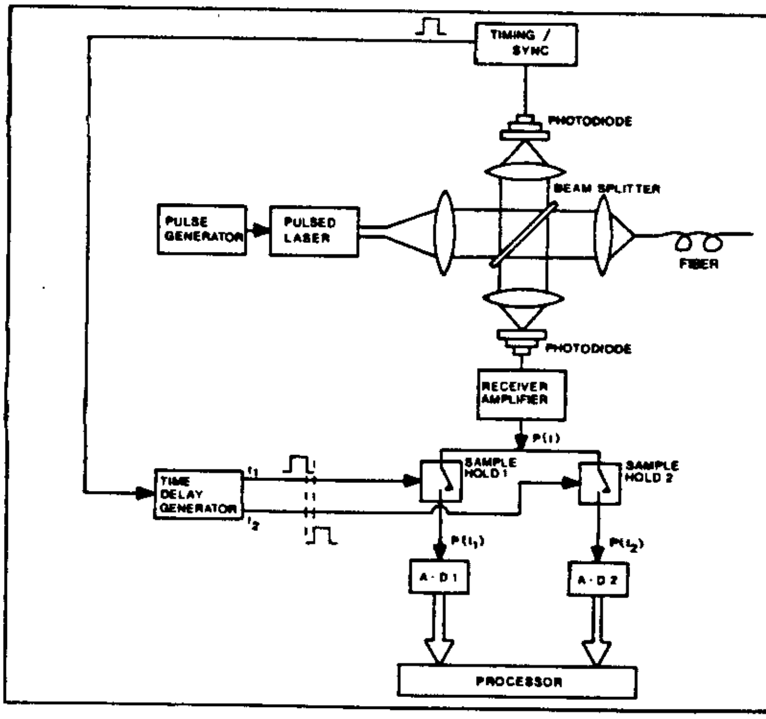


Fig.3: Schematic of the two-point sampling technique for backscatter attenuation measurement.

Another advantage of the two-channel method is that variations in the level of the backscatter signal from pulse to pulse do not affect the accuracy, so that the stabilities of the source, detector and amplifier are rendered unimportant. Hence simple, inexpensive circuits may be employed. Any gain errors in the sampling and conversion circuits can be eliminated by alternating the time windows on the two gates, and the attenuation is given directly rather than by taking the slope of an experimental curve.

To obtain the attenuation characteristics of the whole fiber the sampling times t_1 and t_2 can be scanned to cover the entire length. Fig.4 gives a comparison of the results obtained on the same fiber using (a) the two-channel method, with a tunable source, and (b) the cut-back method. Care was taken to ensure the same launching conditions in the two cases. The agreement over the whole wavelength range 0.82 μm to 1.07 μm is excellent, showing that the two-channel method is capable of considerable accuracy. Furthermore, by making measurements from both ends of the fiber, changes in core diameter can be observed and differentiated from other forms of inhomogeneity.

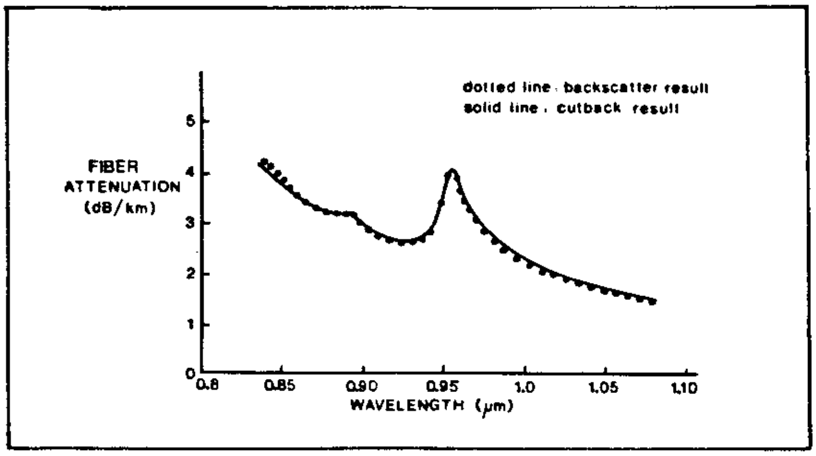


Fig.4: Spectral dependence of fiber attenuation.

Multi-Channel Signal Processing

The two-channel method has proved to be a powerful and accurate diagnostic tool. As indicated above, it scans along the fiber by varying the sampling times t_1 and t_2. It can be improved still further by simultaneously sampling at all time intervals during each pulse and by carrying out multichannel processing. In this modification the complete backscatter signal is digitized at the output of the amplifier in a multichannel digitizer and each of the several hundred channels is then averaged and stored over many laser pulses.

The multichannel method results in a considerable reduction in processing time. As with the two-channel sampling technique the effect of instabilities in the source, detector and amplifier are greatly reduced. The variation of loss along the entire length of fiber is immediately obtained and core diameter variations and other inhomogeneities, including joints, can be observed. The penetration depth with both monomode and multimode fibers can be up to about 40dB.

Conclusion

Backscatter techniques are non-destructive, require access to only one end of the fiber and provide detailed information on loss characteristics as a function of length. The position of faults and poor splices can be determined and another advantage is good repeatability. Changes in numerical aperture, diameter and scatter coefficient can also be detected but interpretation of the results then requires some care.

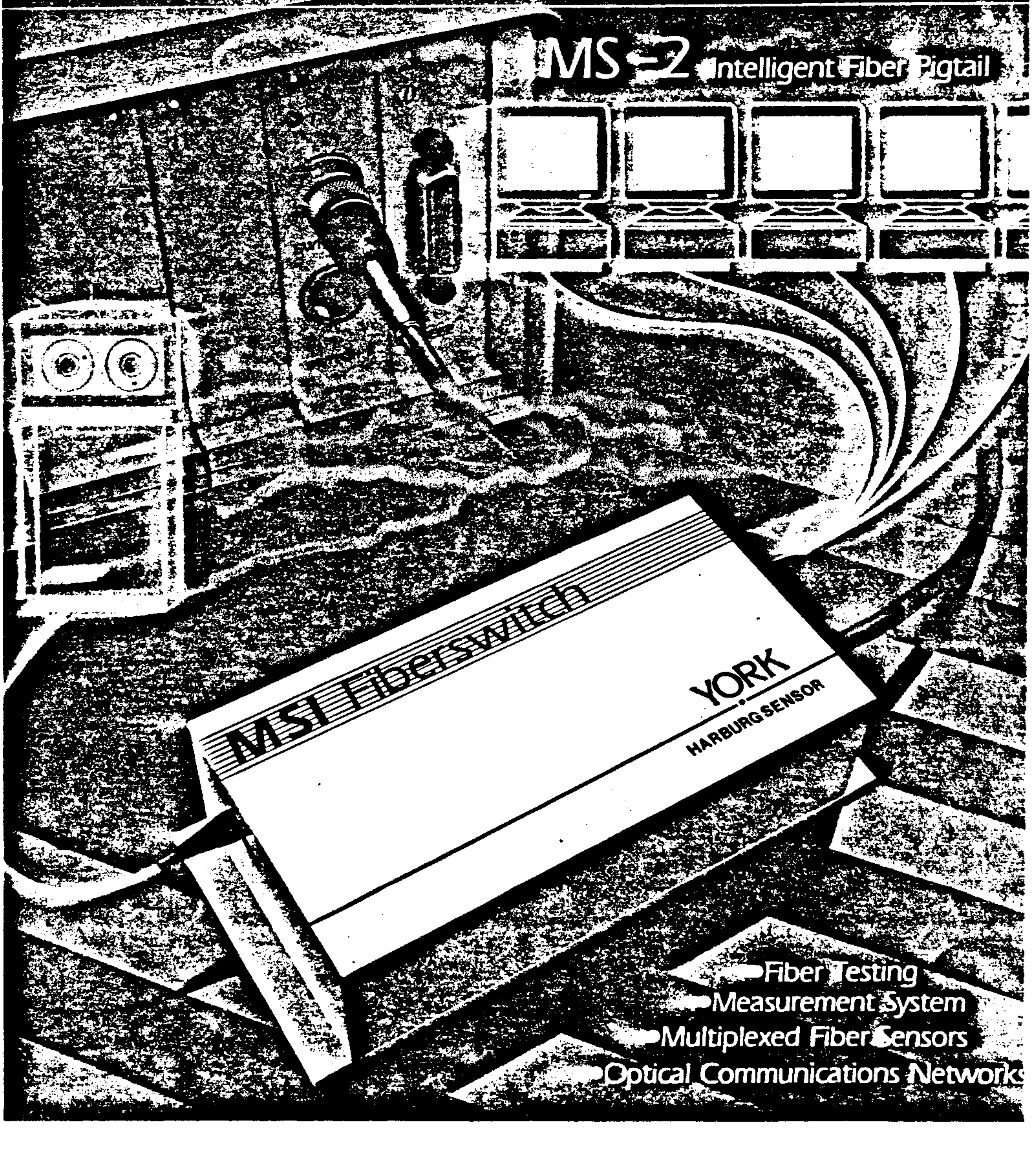
Professor W.A. Gambling
Southampton University

YORK

YORK HARBURG SENSOR

MS-1 Singlemode/Multimode Optical Fiber Switch

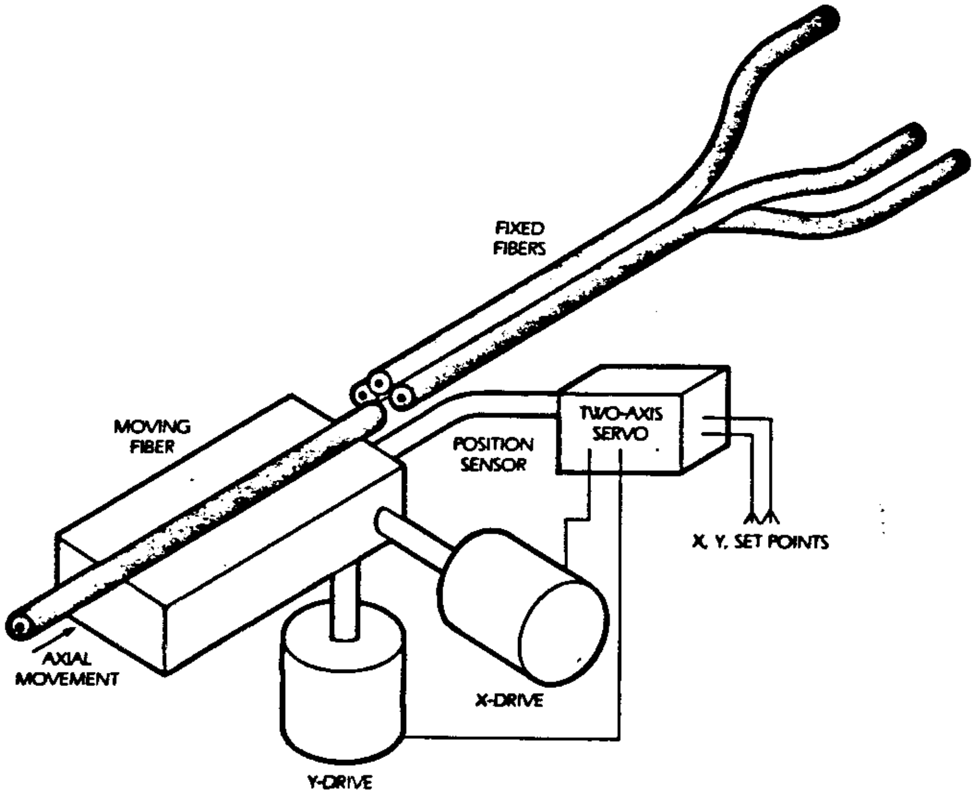
MS-2 Intelligent Fiber Pigtail



- Fiber Testing
- Measurement System
- Multiplexed Fiber Sensors
- Optical Communications Networks

MS-1 Singlemode/Multimode Optical Fiber Switch

COMMUNICATIONS



The MS-1 Multiposition Optical Fiber Switch has been developed to speed and simplify fiber interconnections in laboratory experiments and industrial applications. The device offers unusual precision and stability, making it suitable for both multimode and singlemode components. With an attached computer interface, realistic studies of high speed communications systems and optical sensor networks are possible.

In measurement science, cumbersome and expensive laser, spectroscopic, fluorescence and chromatographic instruments may be multiplexed to a large number of measurement sites and test points.

The MS-1 is a novel, electromechanical, fiber scanning system with the precision and performance to handle the most demanding fiber, including small-core singlemode types. As shown in the above schematic representation, one or more input fibers are supported and moved in two transverse dimensions using miniature linear motors, entirely free from mechanical contact. A precision sensor and two-axis feedback system then allows position control and electronic scanning of the movable fibers, to butt couple one fiber to a number of output fibers. Position resolution and stability of 0.1µm allow optimum coupling adjustment, without the setting problems and hysteresis of convential mechanical stages. As no stops are used, fibers of any cross-section or eccentricity will couple equally well. Coupling loss is essentially limited by the Fresnel loss at the two interfaces.

- **Singlemode/Multimode Capability**
- **Low Transmission Loss**
- **Multiway Switching**
- **High Switching Speed**
- **0.1µm Positioning**
- **Compact Design**

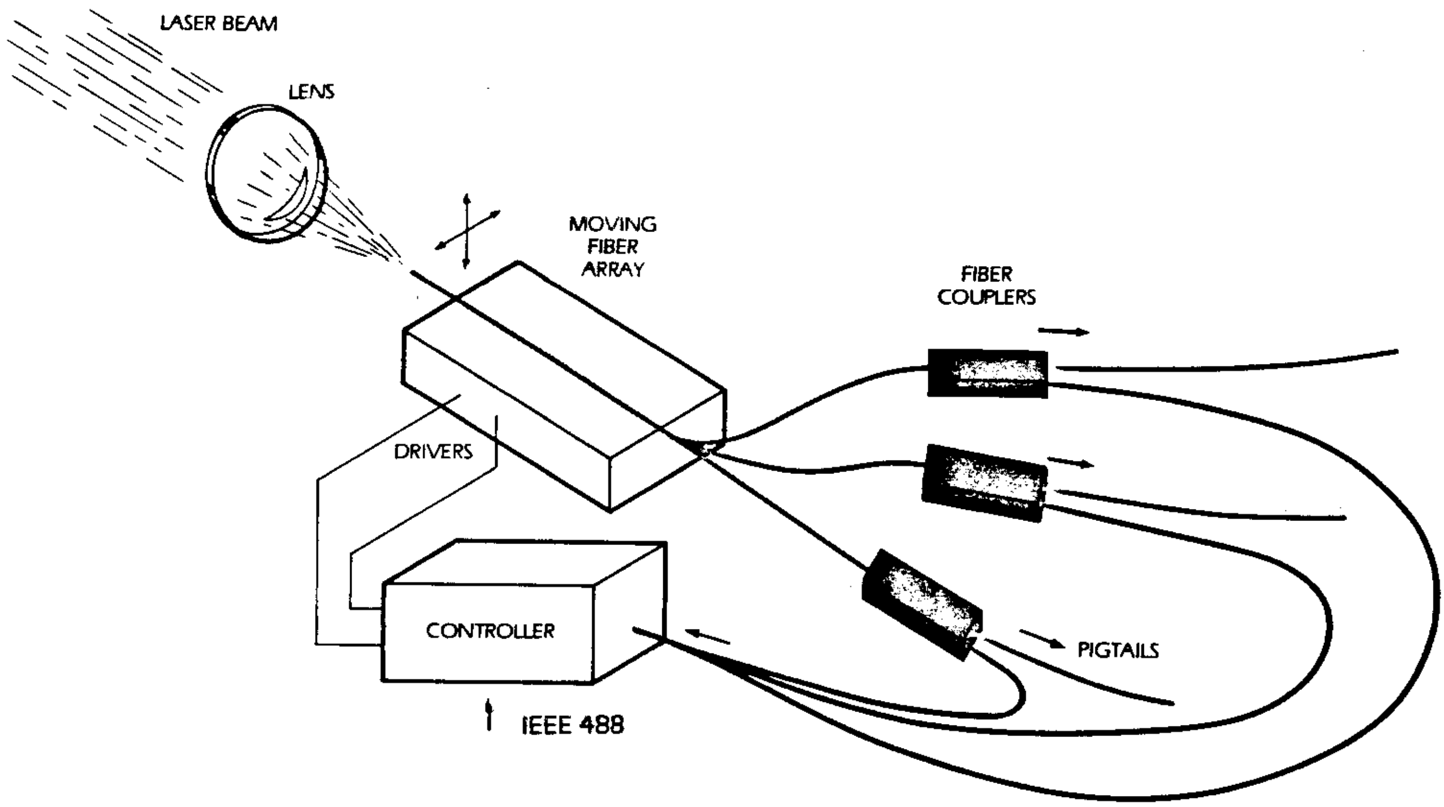
Applications in:

- **Communications Networks**
- **Sensor Multiplexing**
- **Fiber Testing**

The movable fiber position is defined by two analog voltages in the range ±10v; at least 12-bit resolution is required to fully exploit the placement resolution of the unit. Settling to a new position takes typically 5ms, i.e. far faster than stepper motor-driven stages, and without the high voltages and hysteresis of piezodrivers. The unit contains all analog servo electronics for easy integration into OEM systems. A multiway, connectored cable is used to supply power and programming voltages, and to read back the instantaneous fiber position. Alternatively, a power module and computer interface (MC-2) may be obtained to allow connection to computer systems over the IEEE-488 bus.

In this way, a wide variety of commonly-available computers including those of Hewlett-Packard, IBM, Fluke etc. may be used for control. Typical operations are coupling optimization, switching, controlled attenuation, stabilization, and modulation of the transmitted light intensity. Software drivers are available from several manufacturers for use with Pascal, C, and interpreted and compiled BASIC. Example drive programs can be supplied.

MS-2 Intelligent Fiber Pigtail



THE INTELLIGENT PIGTAIL

- Scans
- Tracks
- Optimizes
- Modulates
- Switches

YOUR LASER BEAMS, AND REVOLUTIONIZES

- Doppler velocimetry
- Fiber illumination
- Holography
- Spectroscopy
- Fluorescence studies

Addition of a focussing lens to a high resolution micromanipulator allows no-hysteresis coupling of free-space beams to optical fibers, even singlemode types. The further addition of an optical tap in the form of an in-line fiber coupler makes throughput optimization under digital computer, or analog electronic control possible. The appropriate control signals allow partial coupling, programmable switching between fibers, intensity modulation up to 250 Hz and servoing to external measurement variables.

Essentially all commercially-available fibers may be factory-installed, giving countless combinations of mixed singlemode and multimode fiber outputs, with or without fiber couplers. In this way, great flexibility is possible guaranteeing a wide field of application in measurement science, processing and instrumentation.

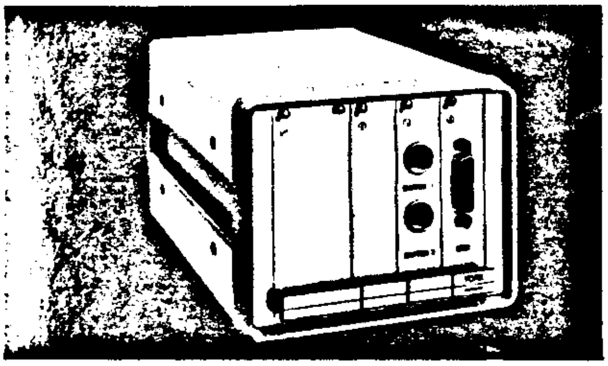
SPECIFICATIONS

MS-1 MULTIPOSITION OPTICAL FIBER SWITCH

Two dimensional electromagnetic manipulator for mechnaical fiber-to-fiber switching. The unit contains the two-axis electromotor and all analog electronics for arbitrary, closed-loop fiber positioning. Only power (±15v 150mA) and X, Y programming voltages need be supplied over the 2 meters long connectored cable.

- Less than 1dB loss with singlemode fibers.
- Switching speed less than 10ms.
- 0.1μm setting resolution.
- ±10v programming input.
- York fiber standard, customer fiber on request (0.63, 0.82, 1.3μm)
- Up to 2 x 6-way switches, larger switches by special order.
- Built-in source and detector fibers for testing/calibration.
- Dimensions 150mm x 80mm x 45mm, with mounting lugs.

MC-2 FIBER SWITCH CONTROLLER



Power unit for MS-1 optical fiber switches, including computer interface to IEEE-488 (1978) standard, capable of driving two switches. Expansion plugins allow drive of up to 6 switches from a single controller address. Allows coupling optimization, attenuation setting, fiber cycling etc. under program control. A positioning command involves sending via the bus two normalized voltage values as ASCII strings. Operation time depends on implementation of the bus controller, and on the language used to access the bus. The new position is established in typically 5ms.

- 12-bit, ±10v X, Y outputs
- 8-bit, 5v measurement inputs
- IEEE-488 Standard; simple command format
- Control from IBM, Hewlett-Packard and other computers
- Software examples for switching, calibration etc. supplied
- 220/240v or 110/120v 50-60Hz line input

MS-2 INTELLIGENT PIGTAIL

Two-dimensional electromagnetic manipulator similar to the MS-1 Optical Fiber Switch except for internal lens for beam-to-fiber coupling. In-line fiber coupler supplies reference signal to MC-3 Detector/Optimizer.

- Hysteresis-free adjustment of fiber in beam-focus.
- 0.1μm settability.
- Coupling optimization via software (MC-2) or continuously (MC-3).
- York fiber standard; customer fiber on request (0.63, 0.82, 1.3μm)

MC-3 POWER OPTIMIZER

Power optimizer including front-panel photodetector connection, low-noise amplifier and real-time analog, peak-searching electronics. May be used with MS-2 Intellegent Fiber Pigtail or as part of a complete system with the MC-2 Controller.

- Continuous intensity differentiation.
- Two-axis power optimization.
- Tracking of wandering laser-beams.

York Harburg Sensor was founded in 1985 to develop state-of-the-art fiber-optic and integrated-optic devices and systems for industrial and laboratory applications. Its staff has an international standing and many years experience in micromechanics, modern optics and electronic control.

The above specification is typical and may be altered without notice in the light of technical advance, component availability etc.

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Teletex: 404 384 = HIT HH
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6/86

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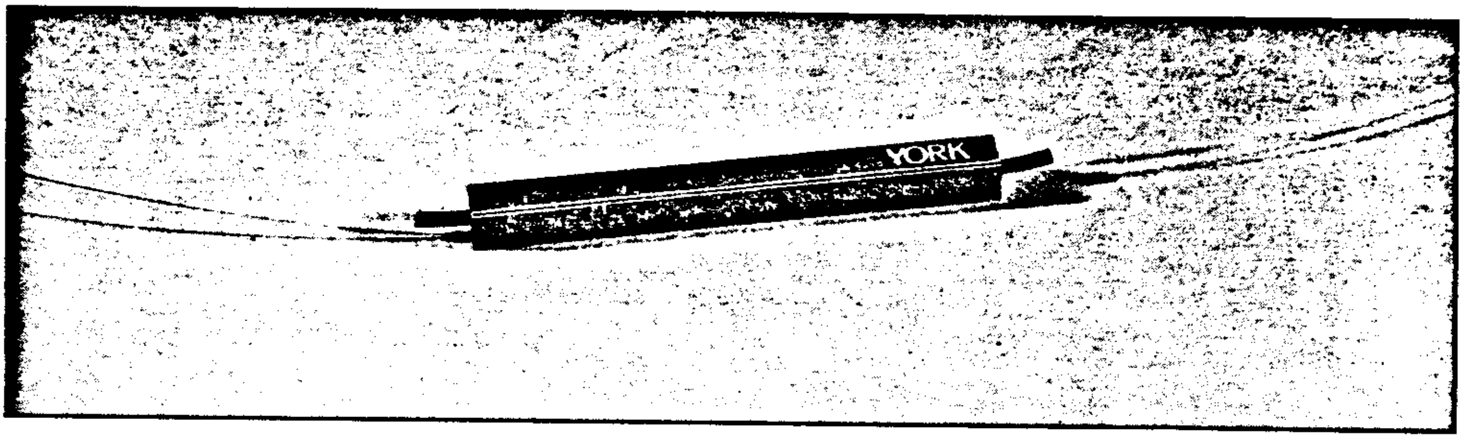
YORK

YORK V.S.O.P.

SINGLEMODE FIBER COUPLER



- Compact, lightweight, rugged design
- Standard splitting ratio 50%, other splitting ratios to custom order
- High directivity
- Low loss
- Thermal stability over wide operating temperature range
- Insensitivity to polarization state
- Attractive quantity discounts

Used for power splitting and combining in:

- Sensors
- Local area networks, communication systems
- Wavelength multiplexed systems
- OTDR
- Fiberoptic instruments
- Other fiberoptic setups

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1601 Swire House, Connaught Rd.
Hong Kong Tel: (5) 269719
Secretary (5) 230011 x 403 Telex 61130

YORK SINGLEMODE FIBER COUPLER

Specifications

	Ultra-high Performance	High Performance	Standard	Non-standard
No. of ports:	2 x 2	2 x 2	2 x 2	2 x 2
Splitting ratio:	50%	50%	50%	a%
Splitting ratio tolerance:	<±5%	<±5%	<±10%	<±10%
Insertion loss:	<0.2 dB	<0.5 dB	<1.0 dB	<1.0 dB
Operating temperature range:	-30 to +70°C	-30 to +70°C	-30 to +70°C	-30 to +70°C
Operating wavelength:	830, 1300 nm	830, 1300 nm	830, 1300 nm	λ nm
Package dimensions:	70 x 6 x 6 mm	70 x 6 x 6 mm	70 x 6 x 6 mm	70 x 6 x 6 mm
Weight:	10 gram	10 gram	10 gram	10 gram
Lead length:	0.75m	0.75m	0.75m	0.75m
Lead Diameter (coating)	250 μm	250 μm	250 μm	250 μm
Lead Diameter (cladding)	125 μm	125 μm	125 μm	125 μm
Model numbers:	SC - 830 - 50 - 0.2 SC - 1300 - 50 - 0.2	SC - 830 - 50 - 0.5 SC - 1300 - 50 - 0.5	SC - 830 - 50 - 1.0 SC - 1300 - 50 - 1.0	SC - λ - a - 1.0

λ is to be specified by the user and is in the range
830 ± 50nm, 1300 ± 50nm.
Other operating wavelengths e.g. 633nm, 1550nm,
are available by special order.

The above specification is typical and may be altered without notice in the light of technical advance.

Couplers with insertion losses
< 0.1 dB now available.

For further information please contact....

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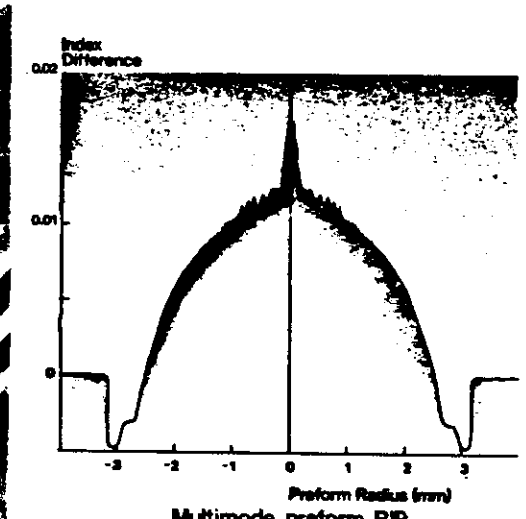
6/85

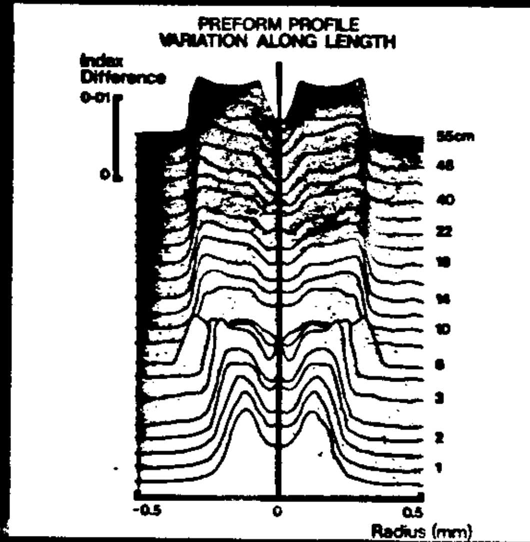
P101

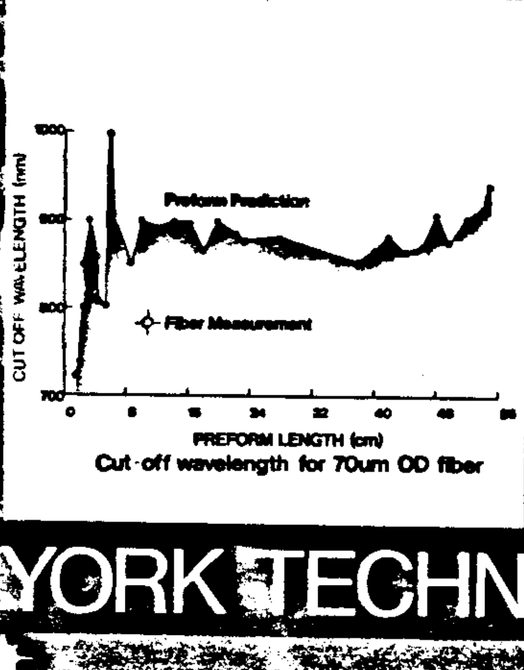
PREFORM ANALYSER

*PATENT APPLIED FOR

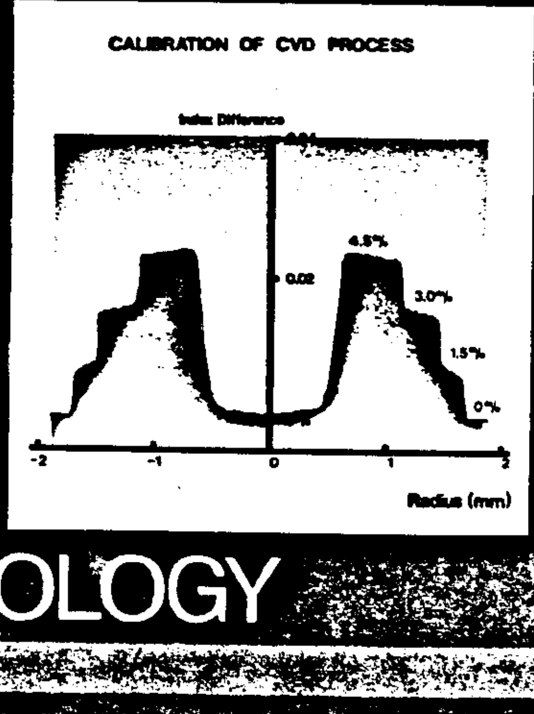


Multimode preform RIP





Cut-off wavelength for 70um OD fiber



YORK TECHNOLOGY

FIBER OPTIC INSTRUMENTATION

P101 PREFORM ANALYSER

The P101 Preform Analyser is a powerful tool for measuring the critical characteristics of optic fiber preforms:

- high-resolution profiles of the refractive index along the length of the preform
- core and cladding dimensions
- ellipticity checks on core and cladding regions
- cut-off wavelength prediction in single-mode fiber preforms

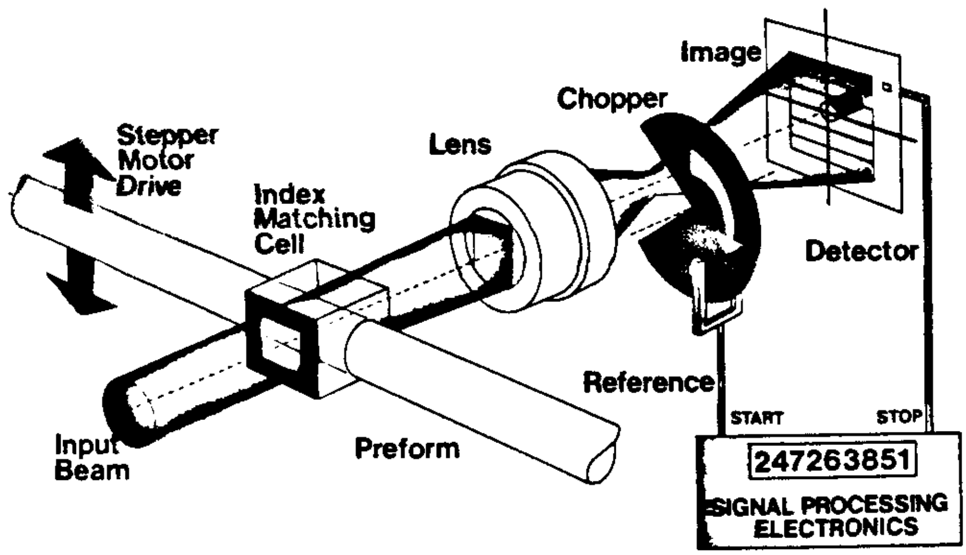
The technique is fast, reliable and entirely non-destructive. It requires no specimen preparation and the measurement can be accomplished by unskilled operators.

The system is capable of high accuracy and high resolution and the interpretation of the results is straightforward. Alternatively, the system can be set for high-speed, limited-resolution operation. It provides, directly and rapidly, data which can be of critical value in calibrating the preform-manufacturing process.

In the production environment the P101 Analyser can be used to drive down manufacturing costs. Because of the close match in characteristics between the preform and the final drawn fiber, the fast and simple procedure immediately establishes the quality of the preform rods and eliminates unnecessary fiber drawing, coating and analysis. The system is applicable to preforms from any of the currently popular processes such as CVD, VAD and others. It is equally useful with graded-index or step-index, single or multimode, preform rods.

FIG 1

DYNAMIC SPATIAL FILTERING

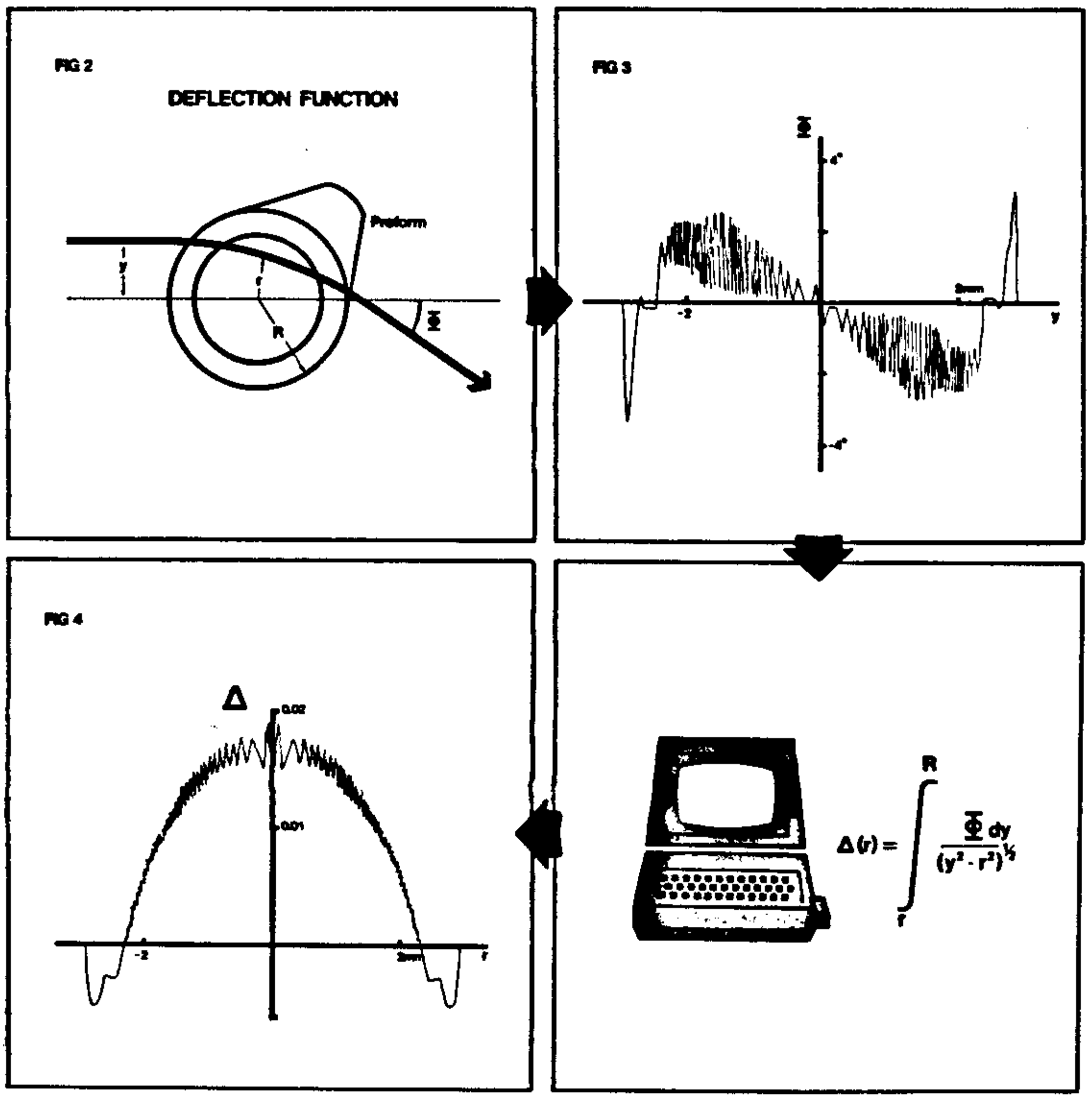


HOW THE SYSTEM WORKS

The system probes the refractive-index profile of a preform rod by means of a well-defined ray of light. It measures the angle of refraction which a light ray suffers on passing through the preform for many positions of the ray in the preform. It then uses this set of data to compute the index profile.

Referring to figure (1), the preform rod is shown mounted in a cell filled with index-matching fluid. A light source generates a beam of well-collimated light. As this light passes through the preform it suffers a refraction through an angle ϕ which clearly depends both on the nature of the refractive-index profile and on the position of the light beam in relation to the preform structure (figure (2)). The lens transforms the angle ϕ to a position $x = \omega \tan\phi$ in its focal plane. The pin diode detector, which is mounted centrally in the image plane, picks up the ray which started from a central source in the object plane of the lens. The spatial filter in the focal plane of the lens selects out this same ray and permits the measurement of the refraction angle ϕ.

As the preform rod is stepped through the light beam a sequence of angles ϕ_n is determined. This sequence forms the data base known as the deflection function (figure (3)) for generating the index profile (see figure (4)).



Refractive-Index Profiles

In figure (5) typical results are shown, taken with the P101 system on a graded-index multimode fiber. The particular example shown demonstrates a flaw in the preform process which was not spotted until the index profile had been scanned.

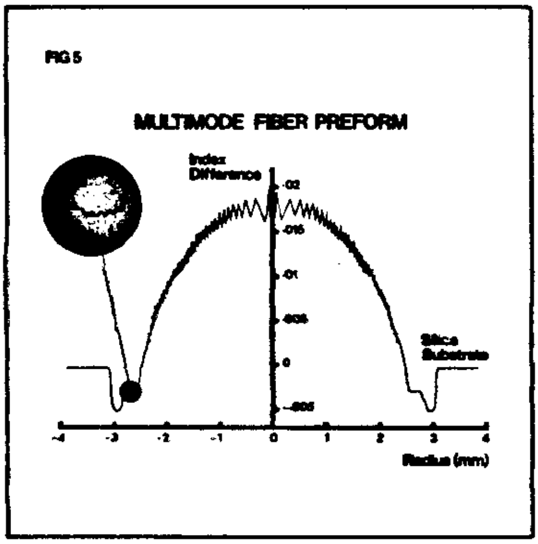
It is clear that the process reveals details of individual layers resulting from a CVD manufacturing process.

The substrate region, the cladding and the core are well identified and quantified.

The central dip in the profile is also very apparent and represents an undesirable feature in the preform rod and is characteristic of preforms made by the CVD method.

Figure (6) shows the result of a series of profile measurements taken along the length of a single mode fiber preform. The figure shows the imperfections which are typical of current preforms, namely a large, central index-depression and a substantial variation of profile along the length, particularly at one end. Fiber drawn from this section would be unacceptable.

Figure (7) is an index profile taken of another preform rod for a single-mode fiber.



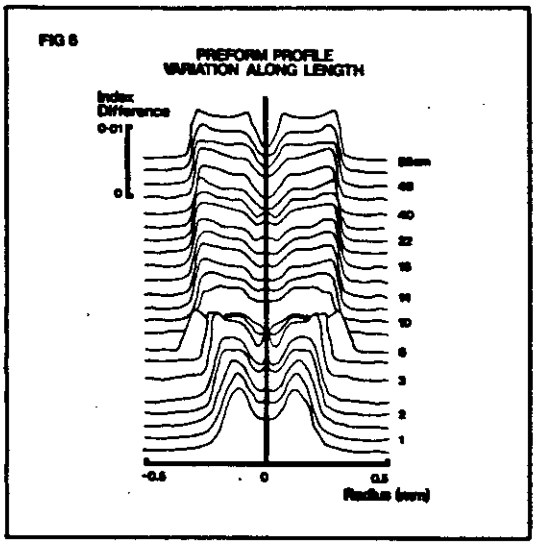


Figure (8) again shows a single-mode preform result. Solid lines indicate the measurements made by the index profiler P101 while the points represent measurements taken by the very laborious and destructive interferometric technique. Agreement is very good.

PROCESS CALIBRATION

Dopant Concentration versus Refractive-Index Difference

Because the refractive-index is related to the dopant concentration, the P101 Analyser provides a direct, accurate means of calibrating the process of preform manufacture. Figure (9) is an example of a measurement of refractive-index difference with dopant concentration as a variable. Each step represents a sequence of deposition layers for a particular dopant concentration and shows the relationship between refractive-index and dopant concentration.

Alternative methods of calibrating the deposition process tend to be indirect, destructive and often require a great deal of time and skill in performing the measurement and interpreting the data.

Cut-off Wavelength Prediction

In mono-mode fiber manufacture the trade-off between numerical aperture and fiber diameter becomes critically important.

The P101 Analyser is a powerful tool not only for speeding up the process development but also in preform checks during routine manufacture.

By calculating the index volume integral from the profile data it is possible to make a number of potentially important decisions about the fiber which can be drawn from the preform:

a) if the fiber is to be drawn to a pre-determined diameter then the resulting cut-off wavelength can be predicted.

b) if the cut-off wavelength of the fiber is to be controlled then the drawing diameter can be programmed.

c) if both fiber diameter and cut-off wavelength are quality control measures then the P101 data will predict whether the resulting fiber will meet both conditions. Hence pre-selection of preforms is possible.

SYSTEM OPERATION

The P101 Preform Analyser system consists of an integrated electro-optic unit and a computer with its control, display, cartridge store and hard-copy facilities.

The P101 unit itself is normally entirely microprocessor controlled and interfaced to the data-collection processing system according to the IEEE-488 (1978) format.

The operator need only load the preform rod in the measuring cell, select the measuring program from a VDU displayed menu, enter the appropriate sample code and the system will automatically proceed with the measurements.

The system software controls the filling of the sample cell with index-matching fluid and positions the preform rod correctly in the light beam. The cell is then stepped automatically through the light beam in step sizes determined by resolution requirements.

When the set of data points has been acquired the cell is brought back to the load/unload position and the fluid drained automatically.

While the system proceeds with data processing, the operator may continue with unloading and reloading the cell. During this part of the cycle a secondary, higher-power, light source is brought into action. This light source allows the operator to examine the deflection function pattern on the front panel screen and makes it possible to optimize the mounting of those preform rods which are not straight. Also the operator may perform visual checks to see that no major defects are present in the preform rod.

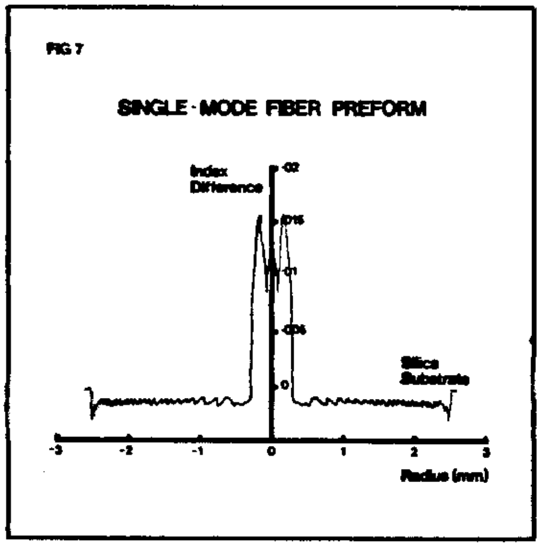
During this stage of the operation the operator is able to check that the system optics alignment is appropriate for the particular preform diameter. Adjustment will be required only when significant changes are made in the diameter of the preform rods.

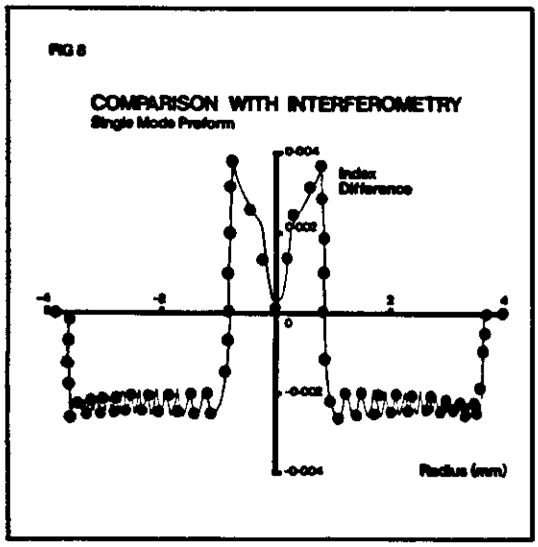
While the system normally requires only the occasional focus adjustment, provision has been made for operator control of cell movement and index-fluid transfer.

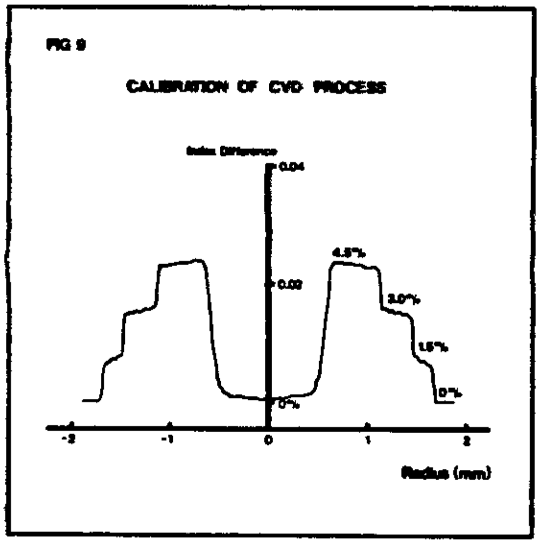
In the standard system the measurement of the index profile at different positions along the preform rod can be achieved by manually advancing the rod through the cell. Rotation of the rod is also a manual adjustment in the standard system.

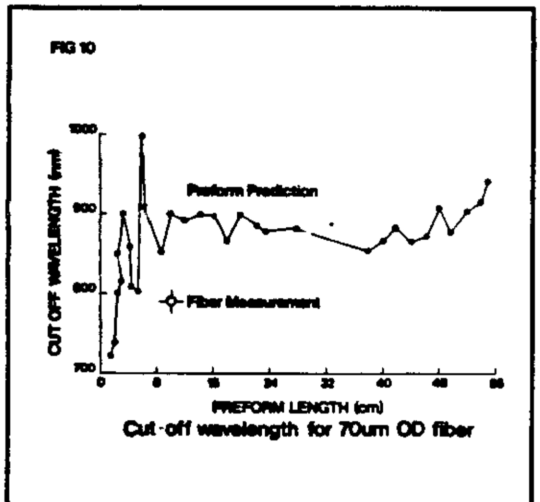
When routine measurements are required of ellipticity (core or cladding), or when a routine examination of a number of points along the length of the preform rod is required then the option 01 – Automatic Preform Advance and Rotation Option – should be included. This option consists of motorized precision translation and rotation stages which are mounted on the cell translation table. It also includes the software required for menu driven computer control.

With the option in place, a complete analysis of a length of preform can be achieved with minimal operator involvement.









Cut-off wavelength for 70um OD fiber

SPECIFICATIONS

Refractive Index

Absolute Accuracy:

Depends on the circularity of the specimen, the nature of the index profile and on the numerical aperture (index difference).

For a high-quality, graded-index, preform rod of NA = 0.2 and with an ellipticity of less than 1%, the refractive index will be specified to better than 0.0005.

For a high-grade, single-mode, preform of NA≃ 0.13 and ellipticity <1% the index will be typically specified to better than 0.0005.

Resolution Maximum resolution better than 20μm.

In general the resolution of the system depends on the number of data points required for a particular preform diameter. The precision linear translation stage is capable of giving a step size of 5μm. A maximum of 1000 points per scan may be selected.

Special values of resolution may be selected from the menu; alternatively the operator may choose one of a number of dedicated programs which will automatically select maximum resolution regardless of preform size.

Specimen dimensions

Preform diameter 5mm – 55mm
Preform length >12cm. Shorter specimens may be accommodated if special care is taken in mounting the specimen in the cell. A special cell attachment may be ordered as an option.

Core and Cladding Regions

The dimensions of the core and cladding regions can be determined in two ways.

The system will automatically interpret the deflection function data to provide these dimensions. These are generally accurate to ±5μm.

Alternatively the operator may perform the measurement by viewing the image of the preform specimen on the front panel screen.

Measurement and Cycle Times

A complete measurement cycle consists of data acquisition followed by a data-processing cycle.

Data acquisition takes place at the rate of approximately 5 points per second. This means that the maximum time taken to acquire a full set of 1000 points is less than 200 seconds.

The data processing time depends on two factors, first on the number of index points required and secondly on the computer speed.

Two computer systems are offered with the P101 Analyser. The more economical solution is based on an HP85 mainframe, interfaced via the IEEE format and with speed enhancement by assembler ROM.

This system is recommended for all applications except where processing speed is the over-riding concern.

As an alternative solution the system can be complemented with the Tektronix 4052. Greater speed and higher-quality graphics display are inherent in this system. For hard-copy output a separate plotter or print unit is supplied (Tek. model 4631).

Data processing cycle times are quoted for both systems as a function of the number of processed data points. Note that the raw data for 1000 points can be stored for future use while performing high-speed, low-resolution, on-line checks.

	Processing Time in seconds	
No. of processing points	HP85 based	Tek4052 based
1000	5750	1500
500	1500	375
200	240	60
100	60	15

Digital Plotter Option 21

The HP85 computer has hard copy and coarse graphics capabilities. For high resolution graphic hard copy the HP7225A plotter is recommended.

Automatic Preform Advance and Rotation Option P101-01

For automatic ellipticity checks, and automatic scanning along the length of the preform rod, the P101-01 unit may be included.

The translation stage will advance the preform rod in programmable increments. Rotation increments may also be programmed with a minimum step of 1 degree.

The system is based on an electronically controlled precision collett, coupled to a linear translation stage driven by a lead screw.

This option is field installable with assistance from a service engineer.

Accessories available

Index-matching fluid. A choice of index-matching fluids is available from York Technology.

Replacement Seals. When reordering seals it is important to specify the range of preform diameters. The seals may be changed without difficulty.

Accessories supplied

Instruction manual, line power cord, spare fuses, one set of cell seals (specify diameter of preform when ordering).

Power Requirements

The P101 will operate from 90V to 130V and 180V to 260V ac, 50 – 60 Hz. Consumption is 200W.

Physical Details

The dimensions are 840 × 360 × 460 mm deep (33" × 14" × 18" deep). The weight is 30 kg (66 lb). Shipping weight is 50 kg (110 lb).

Operating Environment

The model P101 will operate from 15°C to 35°C.

The above specification may be altered without notice in the light of technical advance, component modification etc.

ORDERING INFORMATION

The Systems

System 1

- P101 Preform Analyser, optics and electronic system complete with IEEE 488 interface.
- Software (specify for HP85 or Tek 4052).

System 2

- P101 Preform Analyser, optics and electronic system complete with IEEE 488 interface.
- HP85 computer with 32k memory, IEEE 488 interface, assembler ROM and software.

System 3

- P101 Preform Analyser, optics and electronic system complete with IEEE 488 interface.
- Tek 4052 computer, IEEE 488 interface and software.
- Tek 4631 plotter.

NB In all systems specify the preform diameter to be used.

The Options

- /01 Automatic preform advance and rotation accessory (specify HP85 or Tek 4052 software).
- /11 Index matching fluids (specify refractive index required, minimum order 1000cc).
- /12 Preform cell seals (set of two supplied with stainless steel mounting mechanism, typically the seals will accept preforms of diameter, d ±3mm – specify d).
- /13 Calibrated preform rod section (rod prepared by CVD process).
- /14 Special cell mount for specimens <12cm in length.
- /21 High resolution graphics plotter for System 2, HP7225A.

The Service

Field service contracts providing on-site attention within 3 working days are available by special negotiation. Cost and availability of this contract is dependent upon location.

For further information contact:

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