REFRACTIVE INDEX PROFILE OF A MULTIMODE FIBER (YOLUX)

NEAR – FIELD

Aim

To measure the near-field intensity profile of a multimode fiber and hence its refractive index profile.

Apparatus

Tungsten halogen lamp, assorted microscope objectives (20X, 40X), two XYZ translation stages, two V-groove fiber mounts, a pinhole detector mounted on a translation stage with an output cable for connecting to a power meter, index matching liquid for use as cladding mode stripper.

Theory

The method essentially involves a scan of the near-field intensity distribution that exists at the output end of a short length (typically one to two meters) of multimode fiber, in which all possible guided modes are excited approximately equally by means of an incoherent Lambertian source[1], such as a tungsten halogen lamp (or an LED). It can be shown that the power accepted at any point 'r' in the fiber core from a Lambertian source is directly proportional to square of the local numerical aperture. Evidently, the maximum power P_m that can be accepted by the fiber corresponds to the position r that which the NA is maximum. In an ideal fiber, this point would correspond to the fiber axis i.e. r = 0. However, many real fibers are characterized by an index dip at r = 0 so that the maximum index n_m does not necessarily occur on the axis. In terms of the maximum power $\left(P_m \equiv P(r = 0)\right)$that can be coupled into a fiber is given by

$$\frac{P(r)}{P_m} = \frac{n^2\ (r) - n_{cl}^2}{n_m^2 - n_{cl}^2} \tag{4.1}$$

For small refractive index differences,

$$\frac{P(r)}{P_m} \approx \frac{n\ (r) - n_{cl}}{n_m - n_{cl}} \tag{4.2}$$

If all the guided modes propagate in the fiber without any differential attenuation or mode conversion, which essentially implies that we consider a short piece of fiber which is relatively straight and devoid of any imperfections, then the same power distribution, which was launched at the input end will exist at the fiber's exit face. Therefore, if this near field is scanned by a small area photo detector, the detector output will yield the near-field power distribution of the fiber and hence RIP of the fiber as per Eq. (4.1). However, since the fiber core diameter is typically about 50μm, it is difficult to directly scan the fiber's near-field with sufficient spatial resolution. In practice, therefore, one obtain a magnified image (of a convenient size) of the fiber output end, and this image is scanned by a small area photo detector [1].

Telecommunication-grade multimode fibers are designed to follow the nominal refractive index distribution given by:

$$n(r) = n_m\left[1 - 2\Delta\left(\frac{r}{a}\right)^q\right]^{1/2}, \qquad r < a$$

$$n(r) = n_m[1 - 2\Delta]^{1/2} = n_{cl}, \qquad r \geq a \qquad (4.3)$$

where n_m is the axial refractive index at r = 0, a is the core radius and Δ is the relative core-cladding index difference:

$$\Delta = \frac{n_m^2 - n_{cl}^2}{2n_m^2} \approx \frac{(n_m - n_{cl})}{n_m} \qquad (4.4)$$

q is the index exponent which defines the shape of the core RIP. For example, q = 1 corresponds to a triangular core RIP, q = 2 corresponds to the parabolic core RIP and *q* = ∞ represents the step index profile (see Fig. 4.3).

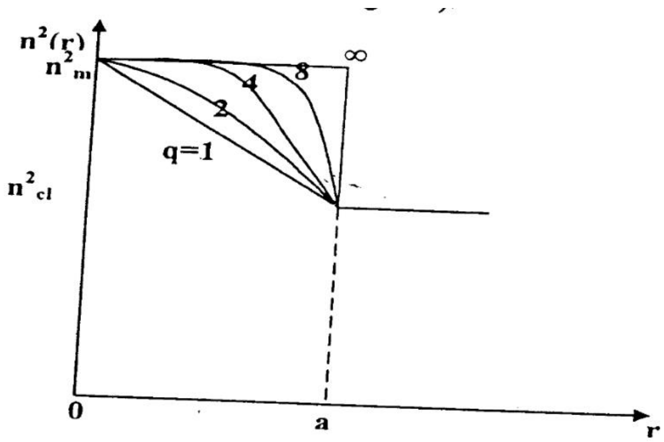

Fig. 4.1 *Refractive index distributions of graded-core multimode fibers described by Eq. (4.3)*

The so-called "optimum profile" corresponding to maximum transmission bandwidth occurs for $q \approx 2$. The exact value of q, in this case, is determined by the material composition of the fiber [2].

Using Eqs. (4.3) in Eq. (4.2) we get :

$$\frac{P(r)}{P(o)} = 1 - \left(\frac{r}{a}\right)^q \tag{4.5}$$

Or

$$log\left[1 - \frac{P(r)}{P(o)}\right] = qlog\left(\frac{r}{a}\right) \tag{4.6}$$

Hence, a log-log plot of [1 – P(r) /P(a)] against (r/a) will yield a straight line of slope *q* and hence the profile shape.
It can be seen from Eq. (4.2) that a measurement of the near field power distribution allows one to determine the refractive index difference [n^2 (r) - n_{cl}^2] except for the unknown constant [$n_m^2 - n_{cl}^2$]. However, [$n_m^2 - n_{cl}^2$] is nothing but the square of the axial NA of the fiber that can be determined independently. Further, if the value of the cladding index n_{cl} is known (which for high-silica fibers may be taken to be approximately 1.46 in the visible wavelength region, corresponding to that of fused silica[1]), absolute values of the indices n(r) can be calculated from the measured near field power distribution.

Experiment

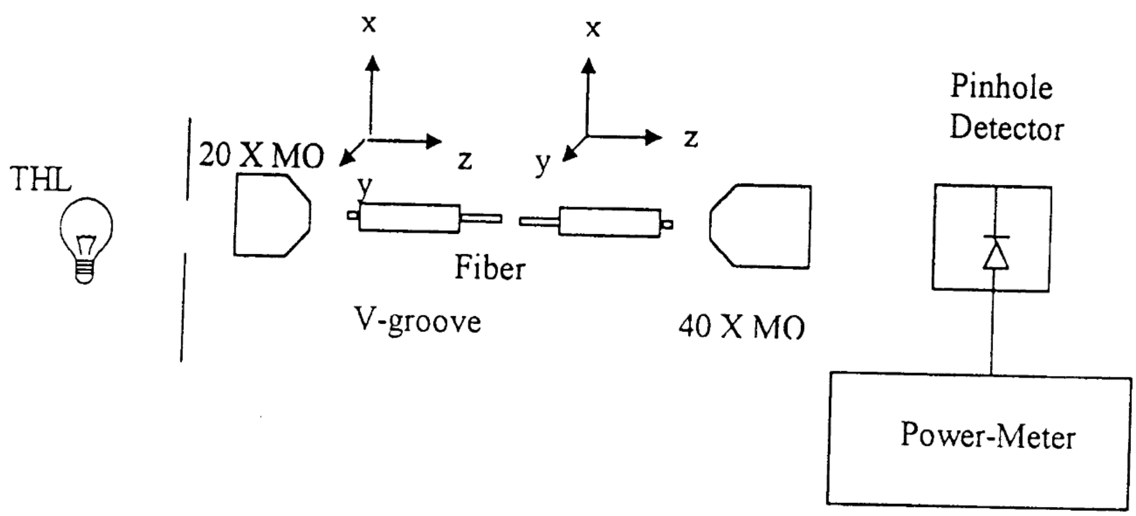

Fig. 4.2 *Experiment set up for near-field measurement of a multimode fiber*

Procedure

The experimental set up is shown in Fig. 4.2.

1. Light from a tungsten halogen lamp (THL), which is an incoherent source of light, is coupled into the given multimode fiber (about 1 meter long) by means of a 20X microscope objective (MO). The NA of the objective should be equal to or greater than the fiber NA in order to ensure excitation of all the guided modes. This launch optics is known to effectively approximate a Lambertian source.
2. The fiber ends are mounted on two XYZ-stacks. It is essential to have a good end-finish of the fiber ends by making good quality fiber cuts. Care must be taken to strip off the cladding modes by applying an index matching liquid, e.g. glycerin or liquid paraffin, over a few centimeters length of the bare fiber, near both the input and the output ends.
3. Using the 40X MO, a magnified image of the output end of the fiber is formed on the scanning plane of a pinhole detector. The pinhole diameter determines the spatial resolution of detection.
4. The detector is mounted on a translation stage in order to scan the image along a diameter of the circular spot of the magnified near field image.

5. To check that the near field image is indeed formed on the detector plane, the following procedure may be followed. For a given position of the detector, the fiber exit face is moved to and fro (using micropositioners) along the axis of the optical system, in front of the imaging microscope objective. The position of the fiber for which the smallest and sharpest image could be seen on a screen coinciding with the plane of the detector will ensure the formation of the near field image on the detector. This is easily understandable on the basis of the wellknown lens equation: $l/u + 1/v = 1/f$ where u and v are the object (in this case, fiber output end) and image distances respectively, and is f the focal length of the imaging MO.
6. The detector output is connected to a power meter. The power meter readings can then be used to construct the near-field of the fiber by plotting power meter readings as a function of position of the detector.

   Alternatively, if the detector is mounted on a motor driven translation stage or a scanner, the detector output could be directly felt to the Y-input of an XY-chart recorder. The near-field can then be obtained directly on the recorder as the 'X-arm' of the recorder is swept along the chart paper. The detector scanning speed and the sweep rate of the recorder should be chosen suitably to obtain a smooth record of the near-field.

Observations:

Value of *a* from the graph =

S.No.	Distance from the fiber axis, r(a.u.)	Power Meter Reading (μW)	Log(r/a)	Log[l-P(r)/P(a)]

Results

The near field profile obtained as described above would be normally symmetric in shape about the central maxima (or minima, for fibers having a dip in the index profile) corresponding to $r/a = 0$. Since there is usually a rounding off at the core edge of the profile, it is difficult to precisely pinpoint the core-cladding interface on the measured near-field profile. This difficulty can be overcome by choosing the x-coordinate at which the near-field intensity drops down by 95% from its maximum value as the reference for $r/a = 1$ (see Fig. 4.3). A plot of $\log[l{=}P(r)/P(a)]$ against log(r/a) will yield a straight line with slope q, the index profile exponent.

In practice, it may be difficult to draw a single straight line connecting all the points due to the profile deviating from a perfect power-law distribution, and a mean value of q can only be obtained by estimating several localized q values corresponding to different small zones of the fiber core. Alternatively, a least square fit of Eq. (4.12) to the measured profile may be carried out to obtain the best-fitted value of q.

To determine the absolute values of refractive indices or the refractive index variation, we need to know the axial numerical aperture. The NA and hence Δ can be estimated from a measurement of the fiber's far-field. The far-field can be measured by removing the imaging microscope objective from the near-field measurement set-up and scanning the resultant output light from the fiber end. Thus, from a knowledge of n and Δ, the measured near-field can be converted to a calibrated RIP by applying Eq. (4.1).

As a final check of the estimated profile, the experimentally obtained values of q and Δ can be used in Eq. (4.3) and a comparison of the measured profile with that given by Eq. (4.3) can be made by plotting the latter also on the same graph.

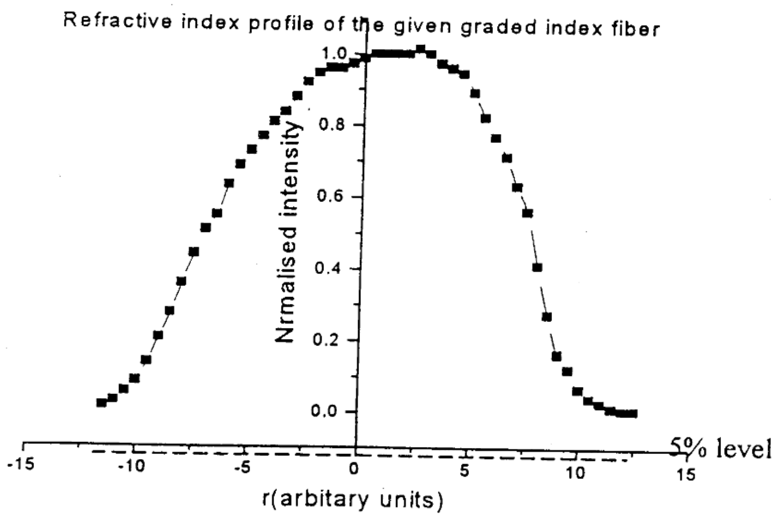

Fig. 4.3 *Typical* results of measurement of the near-field of a graded-core multimode fiber

Discussion

The most attractive feature of the method is that it provides a fast and relatively simple means to get a quick estimate of the core index profile and, for this reason alone, is employed by practically all fiber manufacturers. Nevertheless there is some controversy over the accuracy of the method. It is argued that since a relatively short fiber sample is excited in overfilled (both spatial and angular) launch conditions, the measured near-field may include a significant contribution from leaky rays. One may then by required to take account of this by incorporating a correction factor [3,4] on the right-hand side of Eq. (4.2) in order to convert the measured near-field intensity profile to the fiber's refractive index profile. The presence of leaky rays leads to fiber length dependence of the measured near-field intensity distribution. This problem, however, is not as serious as it may seem because the leaky ray correction factors for a variety of profiles and fiber lengths were found to be almost identical up to a normalized radius *r/a* of 0.8, and differed by roughly $\pm$ 6% beyond *r/a* = 0.8 up to *r/a* = 1. Thus, in practice for a quick general estimate of the RIP, one ignores the presence of any leaky rays in the measured near-field profile of the fiber.

Since, the derivation of Eq. (4.2) is based on the assumption that all modes carry equal amounts of power, care should be taken to avoid (i) any unnecessary stress at the fiber mounts and (ii) sharp bends along the length of the fiber sample. Care should also be taken to center the detector scan path on the fiber axis. Many laboratories use a vidicon with a monitor to scan the near-field. The near-field image of MCVD fibers is usually characterized by a dark central spot (corresponding to an axial index dip), which helps in defining the fiber center. This dark spot also helps the experimenter to check for optimal imaging of the fiber end-face on the detector plane by means of small adjustments in the (z – direction) position of the fiber end in front of the imaging objective so as to obtain maximum contrast in the near field pattern (NFP).

The inherent resolution afforded by the method is

$$\delta r \sim \frac{\lambda}{\pi(fiberNA)} \tag{4.7}$$

For typical multimode fibers NA≈0.2; with λ = 0.65, we get a maximum resolution of about 1μm. On the other hand, detector spatial resolution is set by the size of the pinhole in front of it. If the fiber image size is *l* mm (diameter) at the detector plane and the pinhole diameter is d mm, then the number of independent measurement points on the image plane is roughly *l/d*; thus the resolution limit due to the pinhole is Y = [2a/(*l/d*)]μm, a being the core radius in μm. For high measurement precision, Y should be less than or of the order of the theoretical resolution given by Eq. (4.7); this can be achieved by having a relatively large image produced by a combination of a microscope objective and an eyepiece. However, in a graded – core fiber since the local fiber NA decreases from the core center towards the core-clad interface, there is a loss of resolution in the edges of the intensity profile; consequently, the core edges of the NFP are rounded (see Fig. 4.3). Another point that may be noted while implementing this method is that the emission spectrum of the optical source must be sufficiently broad, or the coherence length of the source should be very small, so that the finite numbers of guided modes do not interfere to produce a speckle pattern at the output end.