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TRAINING COLLEGE ON PHYSICS AND CHARACTERIZATION OF LASERS AND OPTICAL FIBRES

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APPARATUS FOR MEASURING THE REFRACTIVE INDEX PROFILE OF AN OPTICAL FIBRE

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Apparatus for measuring the refractive index profile of an optical fibre

by J.-P. PELLAUX, A. WITSCHI and T. BISCHOFBERGER

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SUMMARY

With the introduction of the method of transmission by optical fibres in the field of telecommunication instruments, there has been a growing need to measure the transmission characteristics of fibres. One of the instruments for measuring the refractive index profile of multimode and monomode fibres is described in this article. From the refractive index profile, the diameter of the core and of the cladding as well as the theoretical numerical aperture can be calculated. It was developed by PROMOGAP in Geneva at the request of the Swiss Telecommunications Administration (PTT).

1. Introduction

It is essential for producers and users of optical fibre cables to measure and verify the optical and geometrical characteristics of the fibres. For example, the quality of transmission by a multimode fibre depends on the bandwidth, attenuation and geometric values, that is, the diameters of the core and of the cladding. In the case of monomode fibres, the cut-off wavelength and the mode field diameter must be taken into consideration. The geometry is made up of a number of parameters which have an effect on the light loss where the fibres are joined. With a view to measuring this geometry, the PTT asked *PROMOGAP* to develop equipment to establish the fibre refractive index profile. This operation allows the diameters of the core and of the cladding, their error of concentricity and the theoretical numerical aperture to be obtained for multimode fibres.

The measuring method used in this apparatus is the "refracted near-field" method which is the reference method recommended by international telecommunication organizations.

2. A short introduction to optical fibre technology

2.1 The optical fibre

Light propagating through a transparent medium such as glass, travels more slowly than in free space. The refractive index corresponds to the slowing-down factor; it is given by the ratio of propagation speed in the air and in the glass:

$$n = \frac{V_{air}}{V_{glass}}$$

When light travels through the interface between two pieces of glass of different refractive indices, not only does it undergo a change of speed but also a change of direction. This is the phenomenon of refraction.

* Translated from *Technische Mitteilungen PTT,* 4/1985.

Particularly, if the light passes from glass of a light refractive index to glass of a lower index, there is a critical angle α_c beyond which the light can no longer pass through the interface (figure 1).

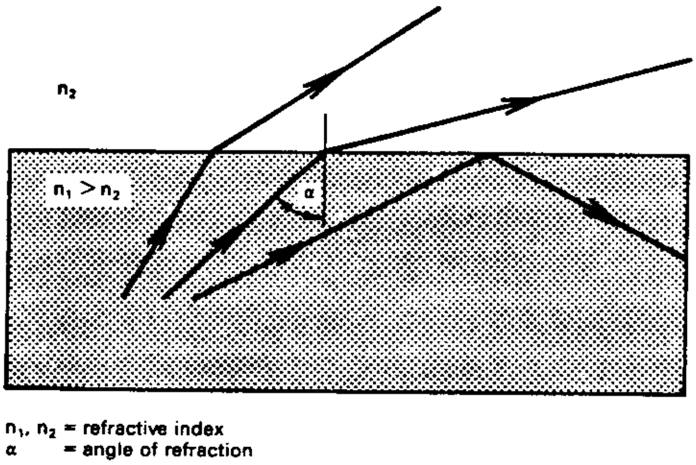


Figure 1—Refraction and total reflection

Total reflection occurs when:

$$\alpha \geq \alpha_c = \arcsin\left(\frac{n_2}{n_1}\right)$$

If, for example, $n_2 = 1.457$ (pure quartz glass) and $n_1 = 1.470$ (quartz glass doped with germanium oxide), $\alpha_c = 82.4°$.

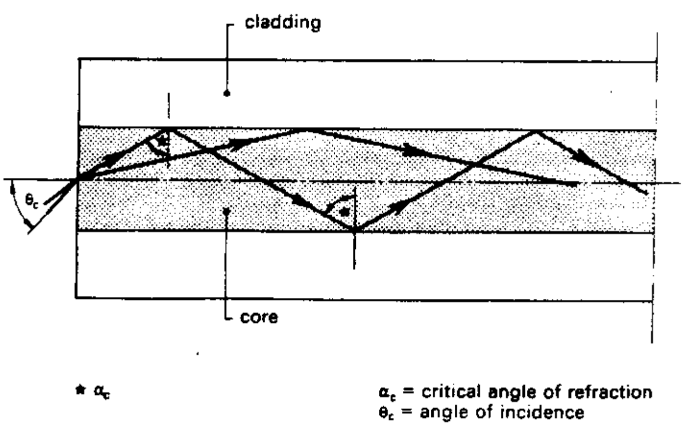


Figure 2—Diagram of the conduction of the light rays

An optical fibre is nothing more than a glass cylinder with a high-refractive index (core) encased in glass of a lower-refractive index (cladding). Light entering the fibre at an angle smaller than θ_c (depending on the critical angle α_c) is then launched into the core of the fibre (figure 2).

The numerical aperture *(NA)* is then given by the launching cone of the light (figure 3).

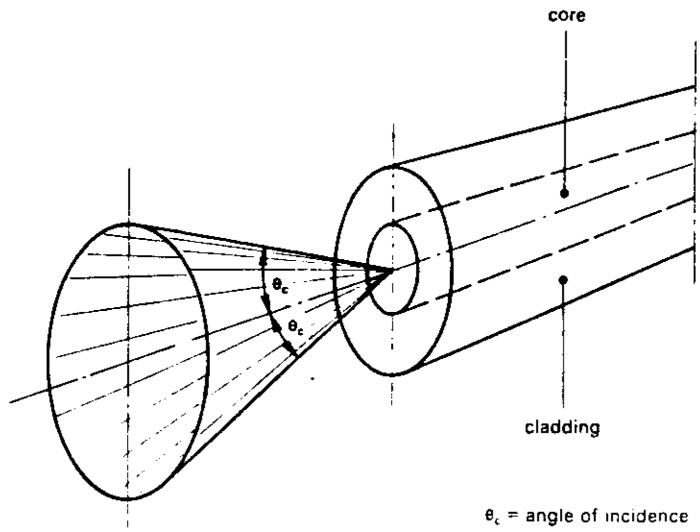


Figure 3—Light launching cone ($2 \cdot \theta_c$)

Three fibre structures are generally used in optical communication systems:

Step index fibres (multimode, figure 4)

The index is constant over the whole diameter of the core (50 to 200 μm). This type of fibre is used in short distance links.

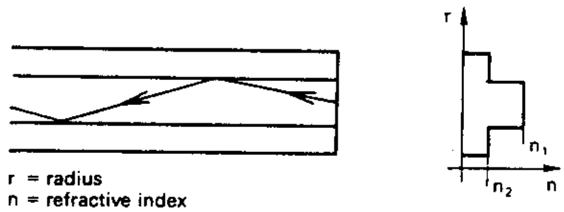


Figure 4—Step index fibre

The numerical aperture is constant over the whole diameter of the core; it is given in the relation:

$$\sin\theta_c = NA = \sqrt{n_1^2 - n_2^2}$$

Graded index fibres (multimode, figure 5)

In the core (typically 50 μm) the index follows a parabolic distribution. The aim of this is to equalize all the "optical paths" of the light and thus minimize the dispersion phenomena.

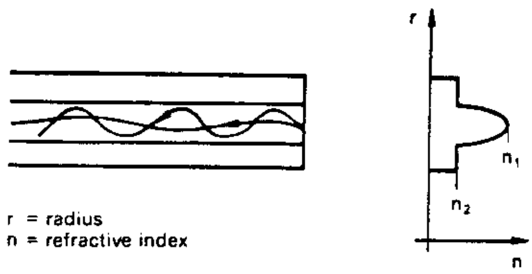


Figure 5—Graded index fibre

This type of fibre is used for average distance links. The numerical aperture is at its maximum in the centre; it decreases to zero as it approaches the edge of the core:

$$NA = \sqrt{n^2(r) - n_2^2}$$

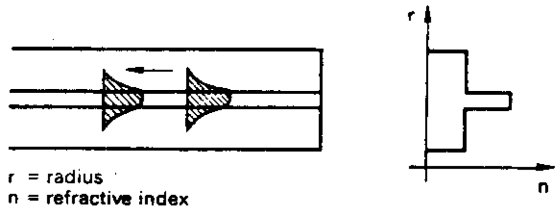


Figure 6—Monomode fibre

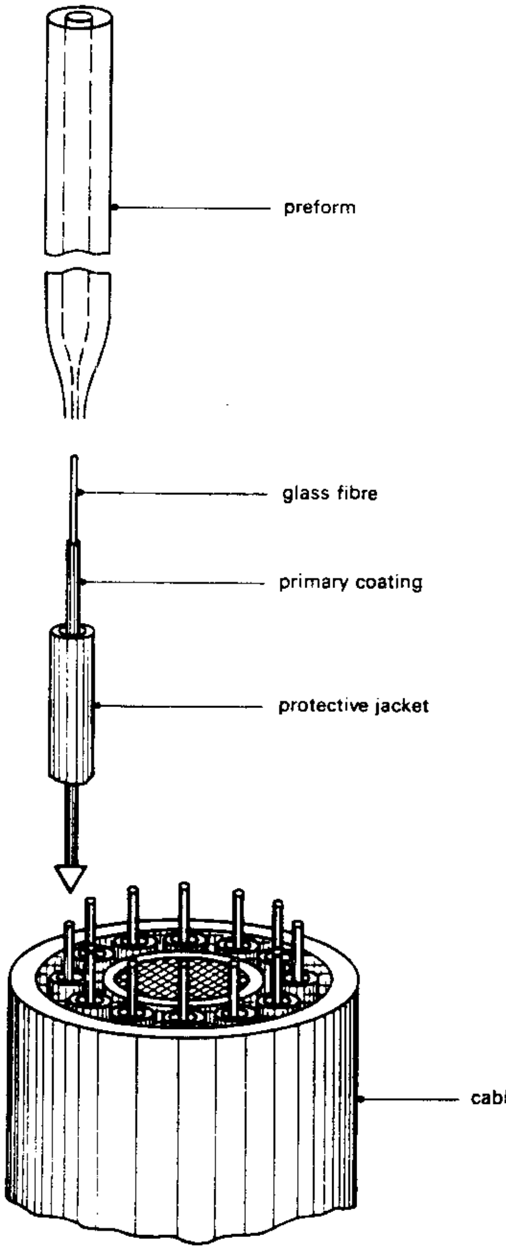


Figure 7—Manufacturing stages of an optical fibre cable

Monomode fibres (figure 6)

The core (5 to 10 μm) is usually a step index ($\Delta n \simeq 7 \cdot 10^{-3}$) only and one "optical path" is possible (monomode). This type of fibre is currently being used in long distance links. Part of the intensity of the light is propagated in the cladding. The numerical aperture only depends on the size of the light spot $2\omega_0$ (diameter of the mode) and on its wavelenth λ, that is $NA = \lambda/\pi\omega_0$.

A typical external diameter of the cladding is 125 μm (monomode and multimode fibres).

2.2 The manufacturing of a fibre optic cable

A fibre optic cable goes through a series of manufacturing stages; the following are the main ones (figure 7):

Manufacturing of the preform

The preform makes up the fibre in its macroscopic form. All the properties of optical transmission are already determined.

The preform is a bar with a diameter of several centimetres and a length of 1 to 2 m. The pre-determined core of the fibre is already positioned along the central axis. The basic material is quartz glass (SiO_2). In order to increase the refractive index, germanium oxide (GeO_2) is introduced, whereas fluorine or boron oxide have the effect of lowering the index. The best-known methods of deposition of the core are:

- modified chemical vapour deposition—MCVD (ITT Western Electric, Cabloptic...);
- plasma chemical vapour deposition—PCVD (Philips);
- outside vapour deposition—OVD (Corning);
- vapour axial deposition—VAD *(Fujikura, Furukawa, Sumitomo).*

Drawing of the preform

Drawing out is an operation common to all techniques. The preform is drawn by the melting of the extremity, thereby producing several kilometres of optical fibre (4 to 100 km). In fact, it is simply a matter of reducing the size of the preform (about 100 times). The drawn fibre is covered with a protective layer (200 μm in diameter) of silicone resin or acrylate. The distribution of the refractive index is retained.

Casing or tubing of the fibre

The fibre is jacketed in a tight protective casing (ITT, Sumitomo, Furukawa, Fujikura, Cabloptic) or enclosed in a tube (*Siecor, Felten & Guillaume,* Cabloptic), both of which ensure the mechanical protection of the fibres. It is possible to introduce several fibres into a tube.

Cabling

The optical fibres are assembled with the tensile elements and then covered with a protective covering forming the cable.

3. The measuring of the index profile

3.1 The index profile

The refractive index profile of a fibre is defined as the set of the refractive index values of a diameter of one section of the fibre. The index profile allowed the structure of a fibre to be known, it is the basic parameter from which certain characteristics of the light launching could be determined (for example, the dispersion, the numerical aperture, the cut-off wavelength or the mode field diameter).

3.2 The measuring methods

The interaction between a beam of light and an optical fibre gives a picture from which the index profile can be calculated.

The lighting can be applied crosswise or along the optical axis of the fibre (figure 8). The originality of the measuring techniques lies in the bringing to the fore of some effects of the index profile upon the amplitude, the phase and the spatial distribution of the light transmitted, as well as in the calculation necessary to find the index profile.

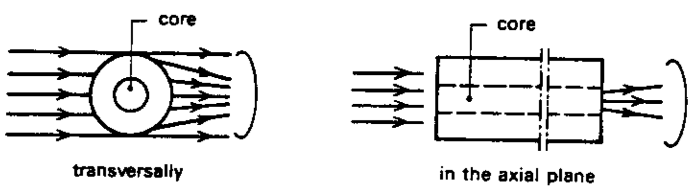


Figure 8—Illumination of a fibre whose refractive index profile is to be measured

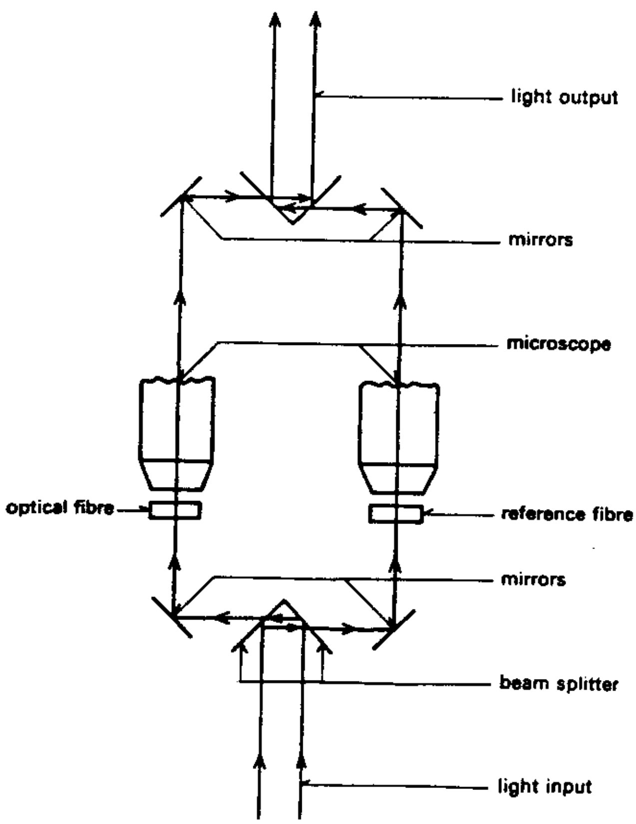


Figure 9—Interferometric microscopy principle (SLAB)

The best-known methods call for the following techniques:

Interferometric techniques: in the analysis by interferometric microscopy (SLAB method in figure 9) and in the analysis by the transverse interferometric method (TIM).

Techniques of transversal spatial analysis: or measure of the deflection of light rays in the method called "focalization" (figure 10).

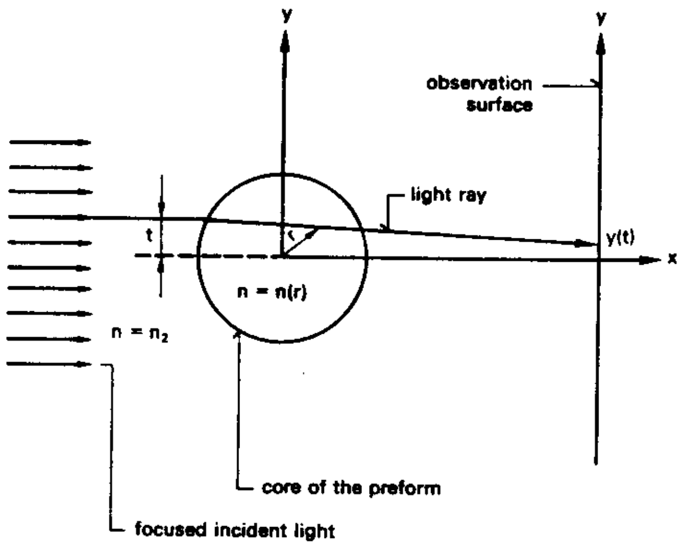


Figure 10—Geometry of the focusing method

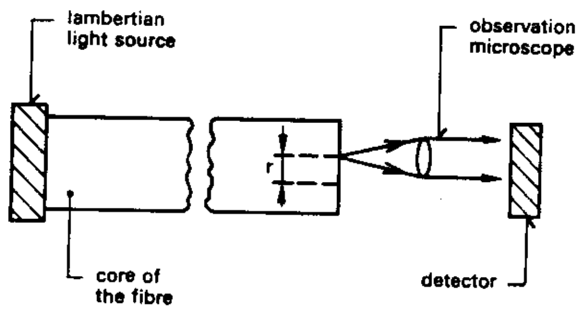


Figure 11—Analysis method of the near-field of a fibre

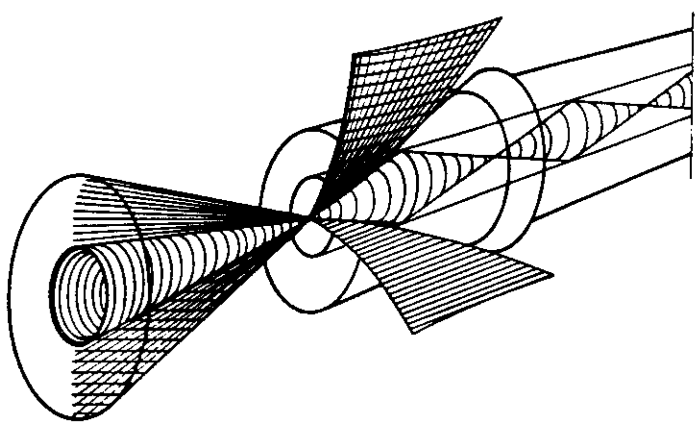


Figure 12—Refracted near-field extracted from the cladding when light injection is larger than acceptance θ_c and when the fibre is immersed in an index fluid

Techniques of longitudinal spatial analysis: or measure of the intensity of the light conducted by the core of the fibre in the "near-field measuring" method (figure 11) or again measure of the intensity of the light which is not conducted by the core of the fibre in the "refracted nearfield measuring" method (figure 12).

Techniques of analysis by light reflection: or measure the intensity of the light reflected by the fibre section. A method which simply follows the basic laws of reflection (Fresnel's laws).

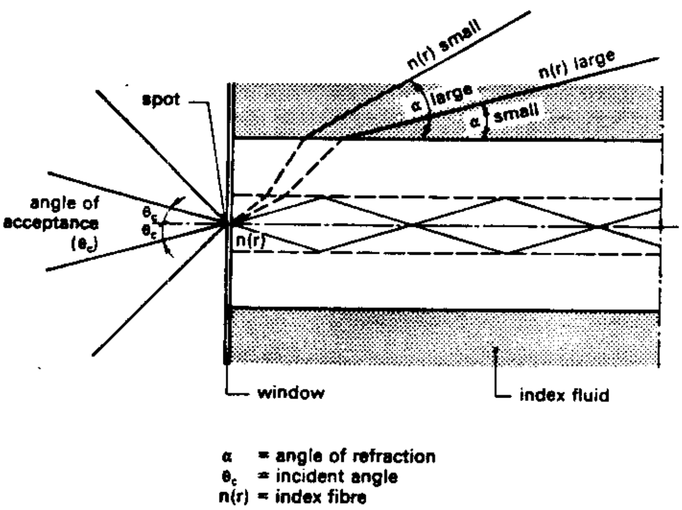


Figure 13—Exit angle (α) of the refracted near-field

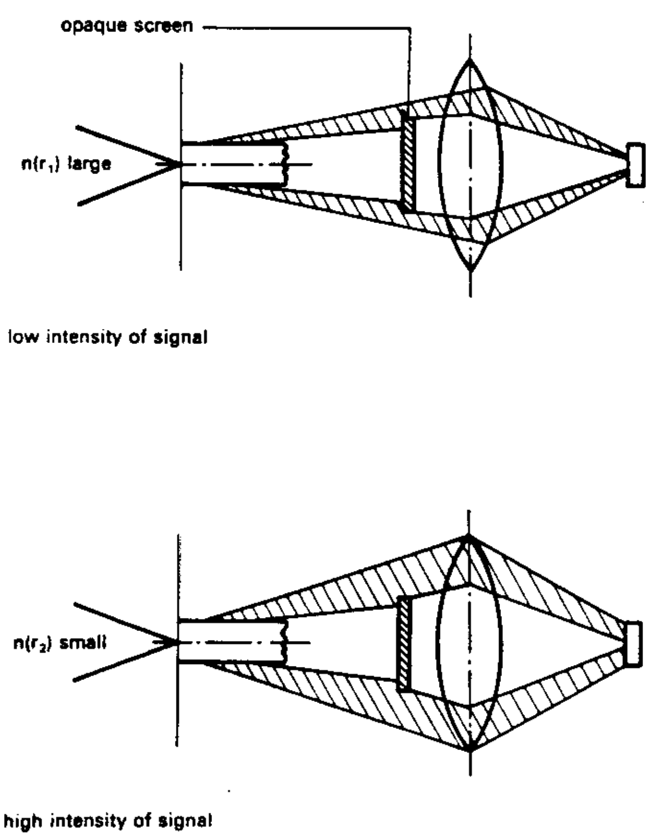


Figure 14—Principle of intensity measurement

The resolutions (refractive index and position) as well as the procedures are different depending on the methods used. Indeed for a measure of the refractive index to be efficiently exploited, it is necessary for the spatial resolution to be at least one micron and for the index value to be measured with an accuracy of 10^{-5}.

On a practical level, the method which best corresponds to these requirements is the spatial analysis of unlaunched light (refracted "near-field" method), as this is shown in figure 12 at a very large numerical aperture ($NA \simeq 0.8$).

3.3 The refracted near-field method

The measurement is taken on a sample of fibre dipped in a fluid whose refractive index n_1 is greater than that of the optical cladding of the fibre n_{c1}. The unlaunched light travels from the cladding into the fluid. The angle at which the light enters the fluid depends on the index value at the point of the spot light; the higher the refractive index at this point, the smaller the angle α. The maximum aperture of the beam of light is thus modified by the value of the index of the measuring point. Figure 13 shows, for example, two cases: one for large $n(r)$ and one for small $n(r)$.

By placing an opaque screen in the core of refracted light and by collecting the light behind the screen, the variation in the width of the cone of light (and therefore of the refractive index) is recorded on the detector as a variation in the light's intensity (figure 14).

The diameter of the screen is chosen so as to let only refracted modes through; it determines the interior cone of light. The exterior cone of light will be wider or narrower depending on the refractive index at the focusing point. The variation in the light collected by the detector is almost proportional to the variations in the refractive index and is given by

$$n_1^2 - n^2(r) \cong K \cdot \frac{P_1 - P(r)}{P_1}$$

where

n_1 is the refractive index of the fluid

$n(r)$ the refractive index to be measured

$P(r)$ the light power measured according to r

P_1 the light power measured in the fluid alone

K constant of proportionality,

which gives, considering the small index variations (0.01):

$$\Delta n(r) = n_1 - n(r) \cong K' \cdot \frac{P_1 - P(r)}{P_1}$$

The calculation of the constant K' constitutes the calibration. This is possible because the index of the fluid n_1 (which depends on the wavelength and temperature of the fluid), is easily measured by means of an *Abbe* refractometer and because the refractive index of one point of the fibre is known, for example n_{c1}, that of the pure silica cladding (MCVD). K' is therefore given by:

$$K' = \frac{(n_1 - n_{c1}) \cdot P_1}{P_1 - P_{c1}}$$

The calibration can thus be made.

4. Conception of the measuring apparatus

4.1 Optical device (figure 15)

• The spot of light under test is obtained by focusing a parallel He-Ne laser beam of about 0.6 μm and with a maximum aperture of about 0.8. A beam splitter directs it towards the measuring cell C, the rest of the light being measured by detector A in order to stabilize the emitting level of the laser (figure 16).

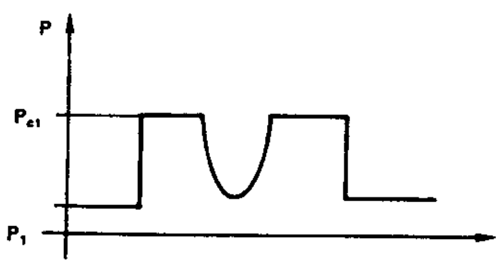


Figure 15—Calibration

• The measuring cell C allows the fibre to be placed in a vertical position against a sheet of glass 0.17 mm thick. This cell contains the fluid and also the detecting device.

• The detecting device D is a simple ring-shaped detector immersed in the cell. The diameter of the central hole was calculated to allow only the refracted modes to be collected.

• The visualization device V uses the lower channel of the beam-splitter; this part of the optical device contains an optical filter which eliminates light from the laser and a lens allowing an image to be formed in a television camera. The fibre is lit up by white light which is launched into it.

4.2 Data collecting

The surface of the fibre under test (window) must be positioned in the focal plane of the microscope lens. The whole cell is then moved horizontally so that it sweeps the fibre section.

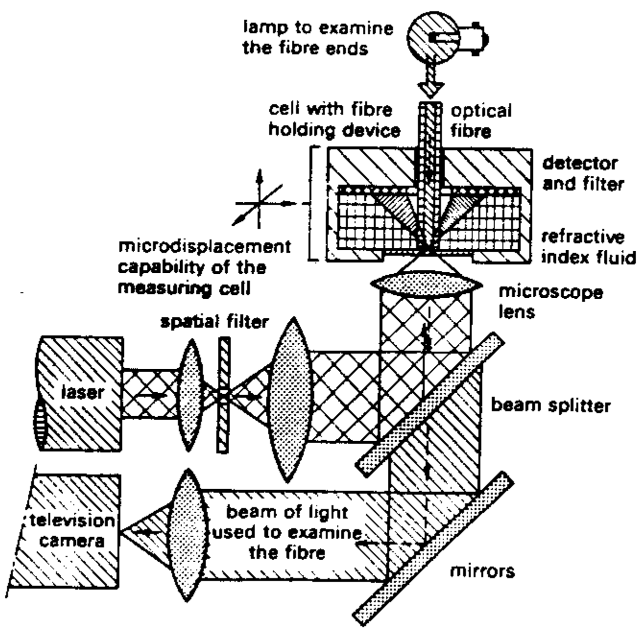


Figure 16—Optical device to measure the refractive index

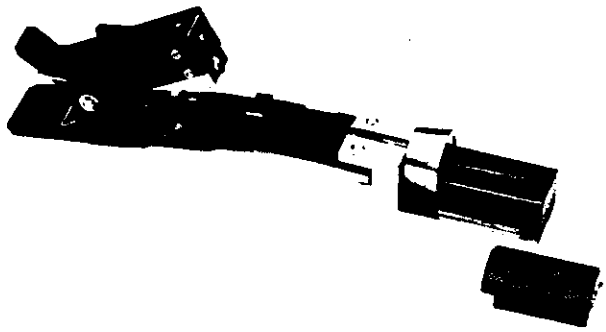


Figure 17—Fibre holder and fibre cleaving tool

This movement is made in 0.1 μm steps by means of mechanized stepping. A microprocessor linked to a calculator by an IEEE 488 bus controls the collection of the detected signal and the positioning of the steps.

4.3 Measurement preparation

Included in the preparation are the cleaning of the cell and its filling with an index matching fluid, the preparation, focusing and centring of the sample of fibre to be measured.

4.3.1 Measuring cell

In optical measuring cleanliness is essential. The window must be cleaned at each filling. However, the use of fluid allows a great number of fibres to be measured.

4.3.2 Index matching fluid

During the handling process the fluid must not come into contact with either dust particles or air bubbles. The fluid was chosen so as to be completely harmless for the user.

4.3.3 Sample of fibre to be measured

After having mounted the cell onto the mechanized stepping device, a sample of fibre without a first coating and several centimetres long can be prepared. It is slipped into the holder made for this purpose and both its ends are simply broken off (figure 17). The break of the section to be measured must be perpendicular to the optical axis of the fibre and its surface of a reasonable quality. The fibre and its holder are then placed in the measuring cell. The fibre is then pushed against the window of the cell and held firmly.

4.3.4 Positioning of the fibre to be measured

The fibre is automatically centred and focused the moment the detector senses its presence. This rough adjustment is made manually by monitoring the end of the fibre on a television screen. Occasionally it does not appear on the monitor screen and in this case an automatic searching process can help the operator to bring the fibre into his field of vision.

5. Practical measures and their results

5.1 Measuring of the refractive index profile

In the first stage the intensity of the light of the refracted near-field is measured on the ring-shaped detector according to the position of the fibre (figure 18).

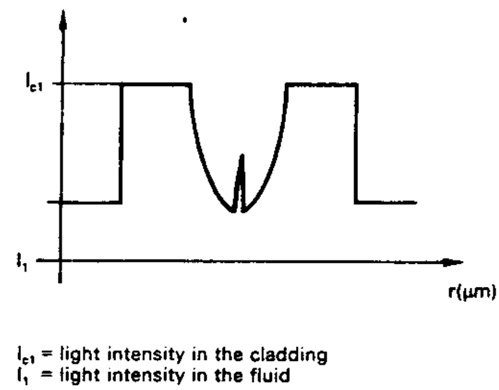


Figure 18—Intensity profile of the refracted near-field on the ring-shaped detector. Example: graded index fibre

The relative variation of the intensity at each point is in exact proportion to the variation in the refractive index. As the refractive index values of the fluid (n_1) and of the cladding (n_{c1}) are known, it is then possible to calibrate and to calculate the refractive index profile from the intensity profile detected (figure 19).

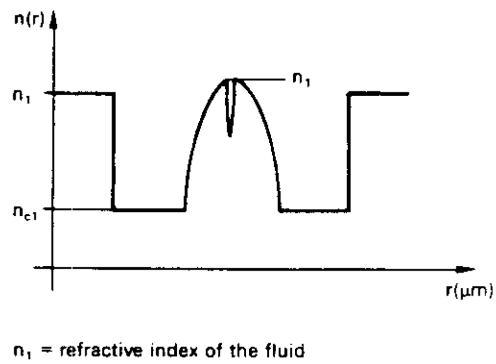


Figure 19—Refractive index profile of the graded index fibre

5.2 Index profiles of several types of fibres

The form of the refractive index profile of a fibre also depends on the method used to manufacture the preforms. Each manufacturing process has its own characteristics (figures 20-25) which are recognizable in each profile. The influence of the different processes on the index profile is described below.

5.2.1 Different profiles of graded index fibres

The core of a graded index fibre presents a quasi-parabolic profile.

Internal deposition processes (figures 20, 21a) and 21b))

The refractive index of the cladding is given by the refractive index of the substratum (tube) of quartz glass (SiO_2). The base layer is an internal cladding. In the MCVD process the layers are deposed one after the other (about 70 to 100 layers).

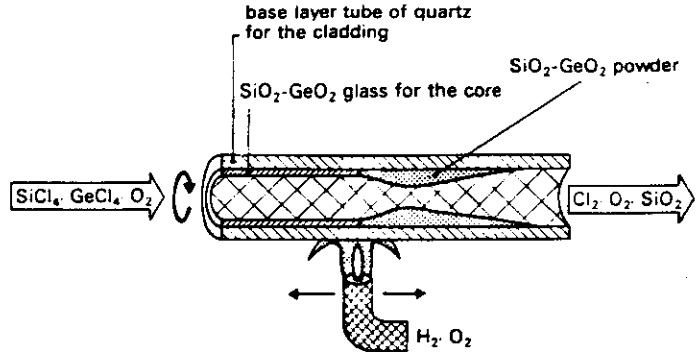


Figure 20—Manufacturing of a preform by the internal deposition process. In the PCVD deposition, the flame (heat) is replaced by an RF generator

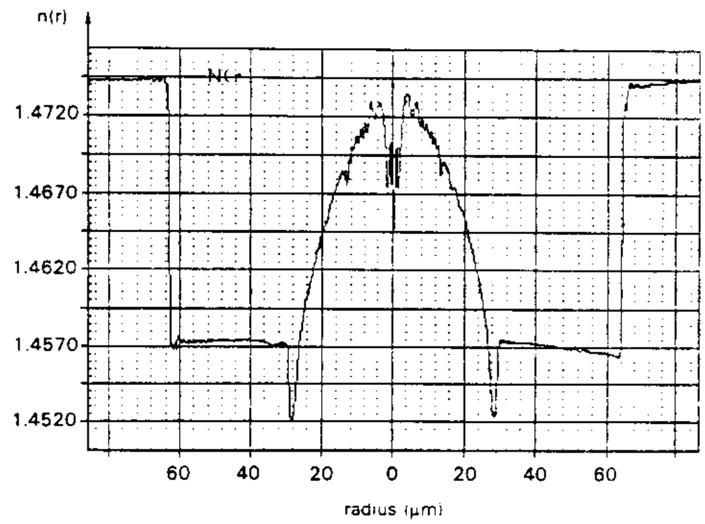


Figure 21a)—Profile of a fibre obtained by the MCVD method

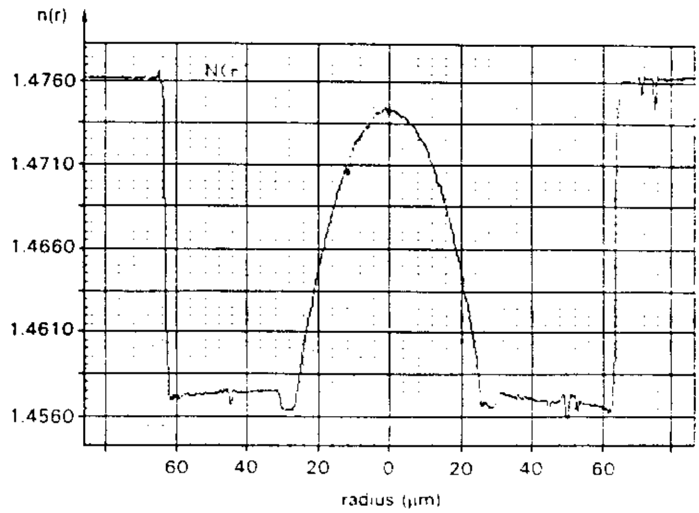
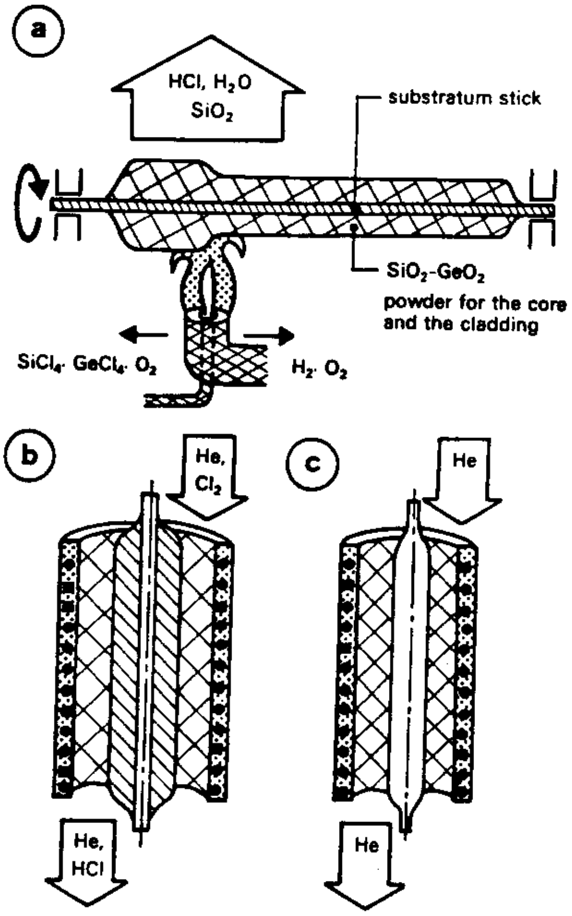


Figure 21b)—Profile of a fibre obtained by the PCVD method



Cl_2 = chlorine
$GeCl_4$ = germanium tetrachloride
H_2 = hydrogen
HCl = hydrochloric acid
He = helium
O_2 = oxygen
$SiCl_4$ = silicon tetrachloride
SiO_2 = silicon dioxide

Figure 22—Manufacturing of a preform by an external deposition tion process (a), *dehydration by chlorine* (b), *collapsing* (c)

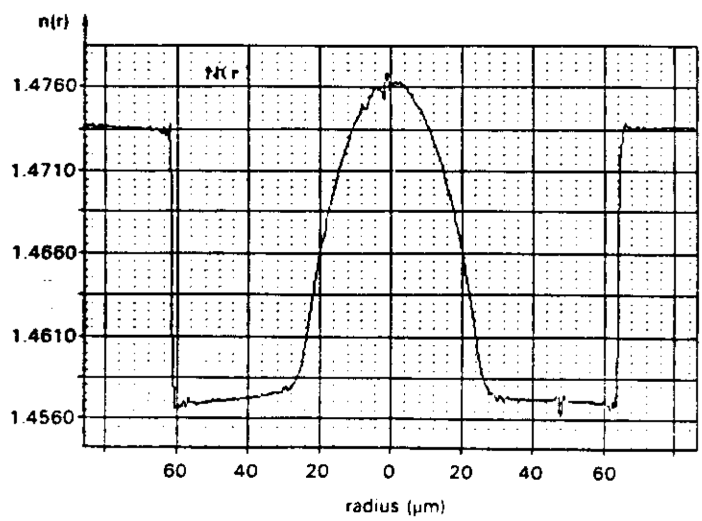


Figure 23—Profile of a fibre obtained by the OVD method

The index of each layer is increased in relation to the previous layer so as to obtain the desired profile.

In the PCVD process the deposed layer grows continuously. Once the deposition is over, the tube is collapsed into a bar. During this operation, part of the doping of the final layer can be evaporated. This brings about a sudden change in the refractive index at the centre of the core (figure 21a)).

External deposition processes (figures 22 and 23)

The cladding and the core are deposed in successive layers onto a fine ceramic stick acting as a substratum. The dividing line between the cladding and the core is not defined exactly. The refractive index of the cladding depends on the doping. This method brings about no step index.

Axial deposition processes (figures 24 and 25)

The core and cladding are deposed simultaneously. The substratum is a revolving disc. It should be noted that the OVD and VAD profiles are very similar. The index profile gives some indirect information about the quality of the transmission, principally about the bandwidth.

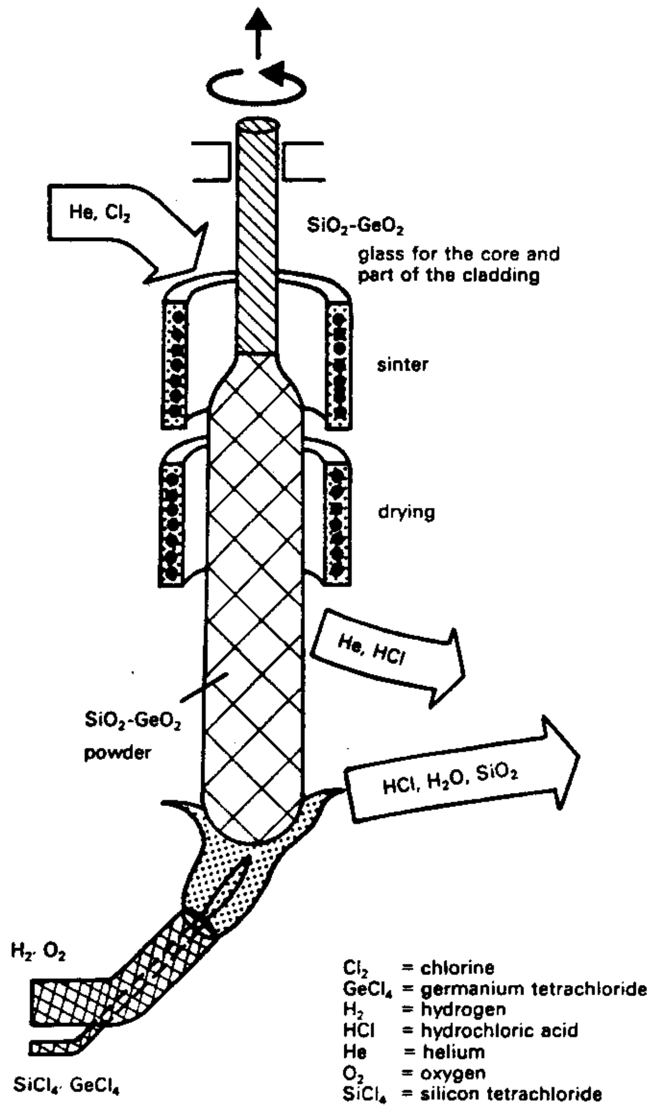


Figure 24—Manufacturing of a preform in accordance with the axial deposition process

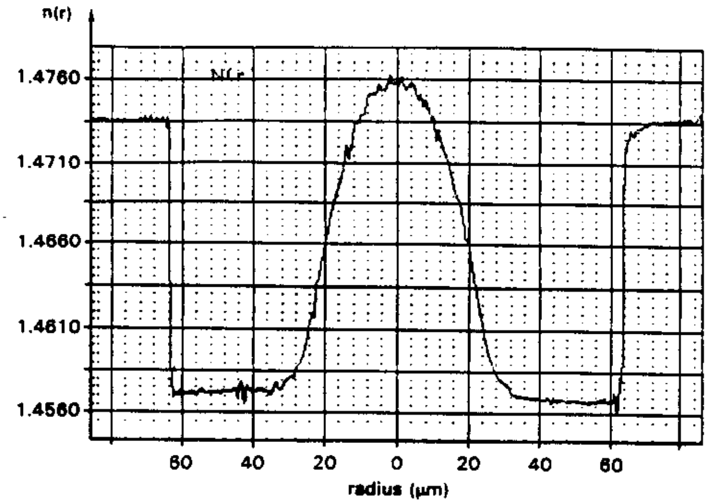


Figure 25—Profile of a fibre obtained by the VAD method

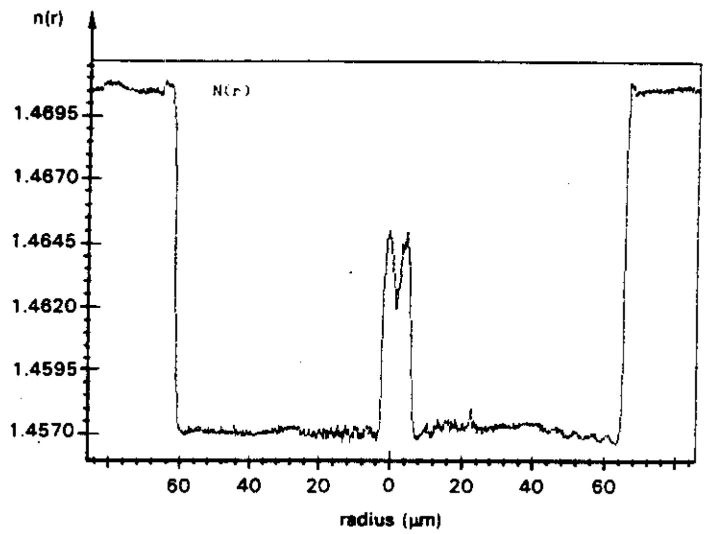


Figure 26—Matched cladding: the refractive indices of the core and the cladding are matched

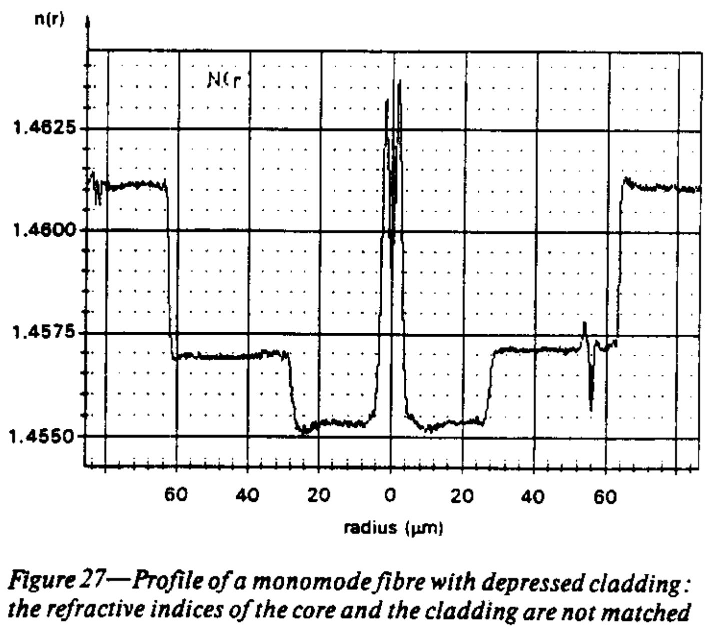


Figure 27—Profile of a monomode fibre with depressed cladding: the refractive indices of the core and the cladding are not matched

5.2.2 Profile of monomode fibres

As a general rule, the monomode fibre used in transmissions with light at 1.3 μm presents a step index profile. Figures 26 and 27 show the types of profile which are typical of monomode fibres.

Starting from the refractive index profile it is theoretically possible to calculate the parameters of the fibre guides (cut-off wavelength λ_c, dispersion, diameter of the mode $2\omega_0$). For the calculation, it is important to obtain a fine measurement in order to obtain an error-free calibration.

5.3 Measuring the geometric parameters of an optical fibre

In order to determine the diameters of the core and the cladding, a series of scannings has to be carried out on the same section of the fibre. Figure 28 shows graphically how this measurement is made.

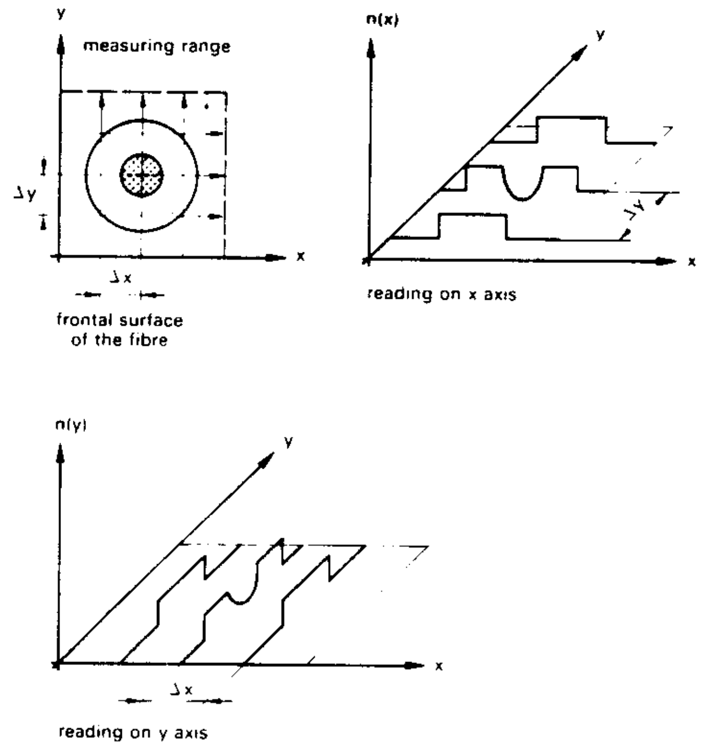


Figure 28—Multiple scannings

5.3.1 Diameter of the cladding

All the points which measure the outside edge of the cladding were chosen to give a 50% difference in the refractive index between the fluid and the cladding. Each point is given by its co-ordinates; the equipment admits measurement steps of 0.1 μm (figure 29).

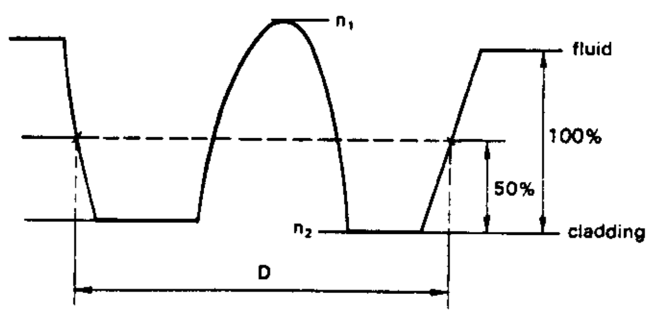


Figure 29—Definition of the diameter of the cladding

5.3.2 Diameter of the core

The diameter of the core of a multimode fibre is defined by the smallest surface inscribed on a line of level of refractive index given as follows: $n = n_2 + K(n_1 - n_2)$, where n_1 is the maximum index of the core or n_2 the index of the cladding near the core, K is a constant with a value of 0.05 (figure 30).

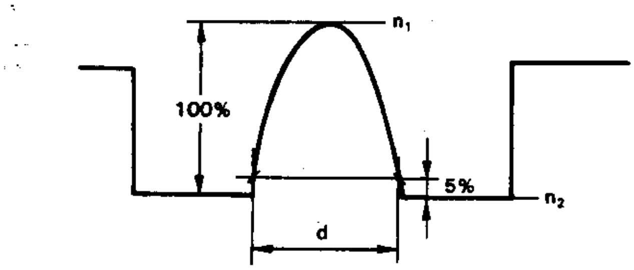


Figure 30—Definition of the diameter of the core

The fibre sectional face is scanned in directions x and y. A refractive index profile corresponds to each scanning. After each measure is taken, the difference between the fluid and the cladding and between the cladding and the core is examined. These give the measuring points for the edges of the core and of the cladding, expressed by their co-ordinates x and y (figure 31).

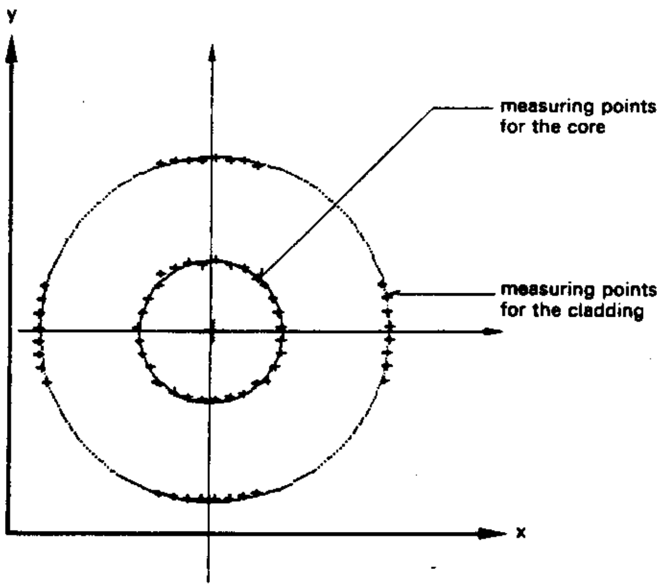


Figure 31—Measuring points for the core and cladding

5.3.3 Utilization of the results

Figure 31 shows all the points which mark the edge of the cladding and the core from which the diameters will be calculated. In the case of the cladding, the optimum circle passing through all the points is determined by the least squares method. This allows the mean diameter D, the statistical error and centre co-ordinates to be calculated.

In the case of the core, the optimum circle or optimum elipse is calculated by the least squares method. The mean diameter of the core (d), its statistical error and its centre co-ordinates are thus obtained.

5.3.4 Core-cladding concentricity error

As the co-ordinates of the centres are known, it is also possible to calculate the core-cladding concentricity error. This is the distance between the optical centre of the cladding (circle of diameter D), and the optical centre of the core (circle of diameter d). It must be either equal to or smaller than 3 μm.

5.4 Maximum numerical aperture (NA) of a graded index fibre

Using the constant of calibration K' defined above, it is possible to calculate the maximum value (n_1) of the refractive index at the centre of the core (for the definition of the *NA*, see paragaph 2.1).

From this index value and that of the cladding (n_2), already known, the value of the maximum numerical aperture of the fibre is calculated (see also figure 30).

6. Conclusions

The measuring of the refractive index profile was considered until recently to be a laboratory operation. The aim of this article is to show that it is also possible to obtain good results using industrial equipment. The operations which are difficult to control have been made automatic in order to firstly guarantee that the results are reliably reproduced and, secondly, obtain the measures in a relatively short time.

The successful production of such an apparatus is due to the collaborative efforts of industry and the Swiss Telecommunications Administration (PTT) and has resulted in the manufacture of an exportable product.

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