

**Optical Fibre Coating Thickness and Geometry -
Report on a feasibility study of traceability issues associated with different
measurement techniques**

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Summary

This study, on the techniques suitable for measuring the geometry of optical fibre coatings, and the issues associated with traceability, has been carried out as required under DTI contract MPU 8/52. The aim of the study was:

- To identify techniques that could be used to make traceable measurements of the geometry of optical fibre coatings
- To examine the traceability issues associated with each technique
- To determine whether the techniques had sufficient sensitivity to meet the industrial requirements identified in the report "Fibre Coating Thickness and Geometry -The Results of a Survey of Industrial Users and Developers"

The study first identified techniques that would be suitable for making traceable measurements. The methods identified were:

- the beam deflection method
- the forward scattering method
- the back-scatter method

The measurement techniques were tested experimentally to gain an understanding of their likely sensitivities. The techniques were also examined theoretically to establish whether the measurement sensitivities were sufficient to enable the fibre coating parameters to be measured with sufficient accuracy. Traceability issues for each technique were also examined.

It was found that the ray-trace method did not give sufficient sensitivity for measurement of the fibre coating parameters. The two scattering methods appeared to have sufficient sensitivity, with the back-scatter method having the greatest sensitivity.

Fibre coating parameter measurements made using the scattering techniques would be traceable. However, the development of the techniques will require a significant amount of theoretical work. The total estimated effort required to develop a fully working facility is 1.5 man-years.

The investment required to develop a traceable measurement system in this area is not justified considering the limited industrial requirement.

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1. Introduction

This study follows-on from a report submitted in December 1999 entitled “Fibre Coating Thickness and Geometry - The Results of a Survey of Industrial Users and Developers”. That report examined the industrial requirement for measurements of optical fibre coating parameters.

The study investigates the traceability issues associated with techniques for measuring optical fibre coating geometry and examines likely candidate methods for fulfilling the requirements found in the survey of industrial requirements.

The study consists of

- A literature survey to establish the techniques currently used to measure fibre coating parameters
- Elimination of methods where stability of the artefact is inappropriate or where the method does not satisfy the criteria for traceability
- Experimental trials of remaining methods in order to gain an understanding of likely sensitivities of the measurands
- Theoretical modelling to establish approximate relationships between the experimental measurands and the fibre coating parameters

2. The Study

2.1. Traceability and usability issues

Traceable measurements allow credible comparisons between measurements made by different organisations or individuals. For measurements to be traceable they must be shown to sit within an unbroken chain which ultimately leads back to the realisation of the appropriate SI units.

For traceable measurements of optical fibre coating geometry to be available to industrial users, several strategies may be employed. The most practical of these involves the user having a fibre or other suitable artefact which has been calibrated by an accredited facility or a national measurement institute (NMI) and which is then used to calibrate their own equipment.

Any calibration artefact developed must be stable under a variety of environmental conditions, instrument independent, and able to provide a level of accuracy suitable to meet industrial need. There are two obvious candidates for use as a transfer standard. These are a coated fibre or a glass artefact with similar geometrical and optical properties to a coated optical fibre.

A glass artefact would be the favoured option, providing resistance to chemical attack and long-term mechanical stability. However, many commercial instruments require the artefact to be flexible for loading and unloading, thus precluding a rigid glass artefact. No universal glass artefact exists at present, although NIST have recently made available a Standard Reference material (SRM) providing traceability for outer coating diameter measurements. For a multi-layered artefact of more general use, new fabrication techniques will have to be developed.

A coated fibre standard has a number of draw-backs. The coatings are soft and can be susceptible to chemical attack, which may change their geometry. The index matching oil used by most

commercial systems is likely to affect the coating geometry. Coated fibres have also been seen to change their dimensions with age, possibly due to continuing curing of the polymer components over fibre lifetimes.

Fibre coatings are difficult to cleave or polish without introducing distortions to the coatings. Figure 1 shows a cleaved coated fibre. The cleave damage can be clearly seen. The cracks in the coating and the de-lamination of the coating from the cladding would render any geometrical calibration useless.

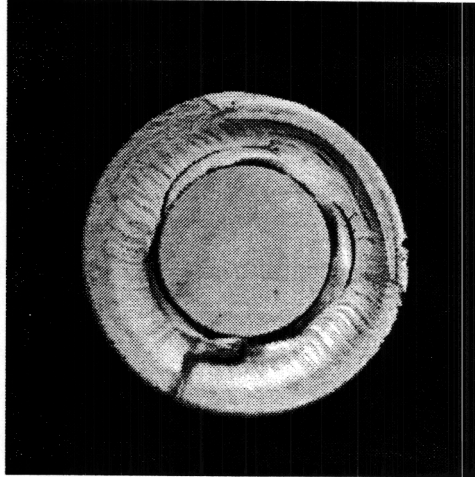


Figure 1. Image of a cleaved fibre end

Figure 2 shows four coated fibres which have been embedded in epoxy resin and polished. Differential polishing and distortion of the soft inner coating, are evident.

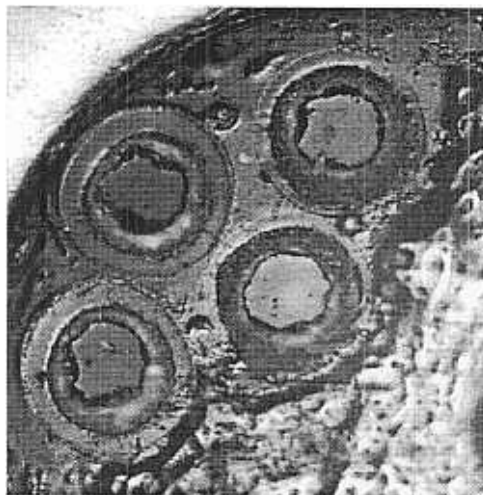


Figure 2. Image of four polished fibres

If a coated fibre were to be used as calibration standard artefact, it should not be measured by a method that involves cleaving and it should not be used with a refractive index immersion oil unless, at the very least, exposure to the oil is brief and the fibre is cleaned afterwards without distorting the coating. Some combinations of matching oil and coating material are known to be more stable than others but the onus must be on the user to demonstrate that continuing, long-term

exposure, does not affect the geometry. The rate of ageing should be taken into account when setting the re-calibration period.

The establishment of these two transfer standard artefacts must take into account the weaknesses of each type. This suggests a method that does not involve a refractive index immersion oil and does not involve cleaving the fibre. This would preclude calibrating inked fibres where the fibre must be cleaved since the fibre coatings are opaque.

2.2.Literature search results

A literature survey was conducted to establish the techniques used to measure the various fibre coating parameters. The survey included scientific papers from journals, published and draft standards documents, and conference reports.

The techniques identified included:

- side-view microscopy ¹
- side-view grey-scale analysis ¹
- side-view ray tracing ¹
- side-view laser scanning ¹
- filar eyepiece ¹
- end-view grey-scale ¹
- butterfly filter ⁴
- reflectance ⁵
- near field intensity⁵
- refracted near field ⁵
- axial interferometry ⁵
- focussing method ⁵
- transverse interferometry ⁵
- back-scatter ⁶
- forward scattering ⁷
- refractive index tuning ⁸
- miscellaneous scanning spot techniques ^{9,10,11}
- white light interferometric location of boundaries.

References are given in Appendix B.

Based on the previous discussion, most of these techniques can be rejected because they require either refractive index matching oil or that the fibre be cleaved. The white light interferometric location of boundaries is also rejected since it requires knowledge of the group indices of the fibre coatings, which are not generally known with sufficient accuracy. The focussing method is rejected because, although it can be carried out without using matching oil, this would require the detection of light over too wide a range of angles and consequently, would be difficult to implement.

The remaining methods are:

- beam deflection
- forward scattering
- back-scatter

3. Description of techniques

3.1. Beam deflection

The schematic layout of the experiment implementing the beam deflection technique is shown in figure 3.

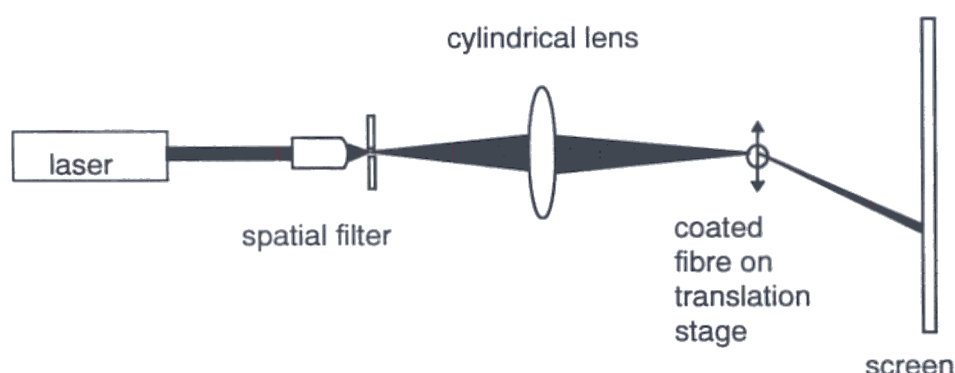


Figure 3. Experimental set-up used for studying the beam deflection method

Laser light is focussed into the coated fibre to give a narrow beam-waist at the centre of the fibre. The fibre and coatings act as a complex cylindrical lens system consisting of non-circular and non-concentric elements which refract the light. The deviated light is detected by a position sensor and the angle of deviation is calculated from the geometry of the experiment. The coated fibre is scanned across the focussed spot and the variation of the deviation angle with input ray offset is recorded. The variation of deviation angle with position (the deflection function) gives information about the refractive index distributions within the fibre, from which the geometry of the different layers can be obtained. Scans are taken at a number of orientations of the fibre to determine the circularity and concentricity of the fibre coating.

3.2. Forward Scattering

The schematic layout of the experiment to implement the forward scattering technique is shown in figure 4.

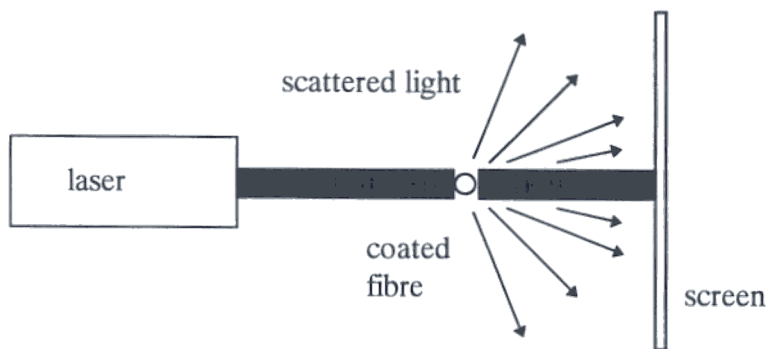


Figure 4. Experimental set-up used for investigating forward scattering

The coated fibre is illuminated with collimated laser light. The light scattered by the fibre in the forward direction is detected by a sensor such as a CCD camera or a detector mounted on a goniometer. The complex scattered light pattern consists of a series of bright and dark bands of varying intensity and angular spacing. This pattern contains information about the refractive index distribution, and hence geometry of the different layers, within the coated fibre. Here too, scans are taken at a number of orientations of the fibre to determine the circularity and concentricity of the fibre coating.

3.3.Back-scatter

The schematic layout of the experiment to implement the forward scattering technique is shown in figure 5.

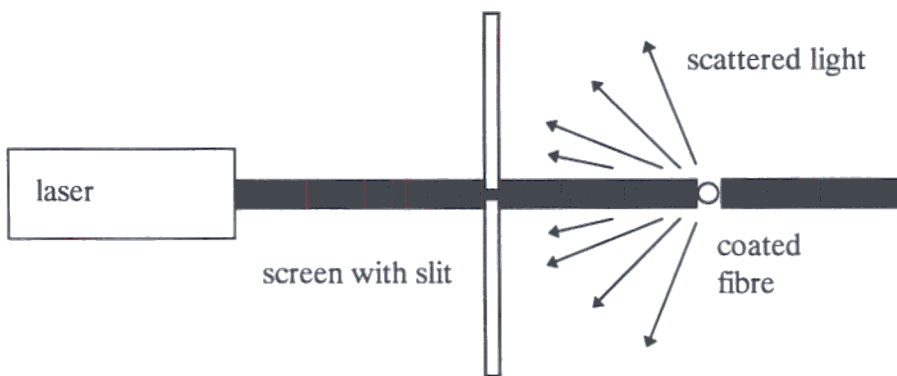


Figure 5. Experimental set-up used for investigating back-scatter

This is similar to the forward scatter method but here the light of interest is scattered backwards in the direction of the source. The light is detected by the sensor such as a CCD camera array or detector mounted on a goniometer. The refractive index distribution in the fibre is obtained from the angular position and the relative intensity of the peaks. As with the previous two methods, scans are taken at a number of orientations of the fibre to determine the circularity and concentricity of the fibre coating.

3.4. Experimental tests

Simple experiments were performed using the three techniques to find the approximate uncertainties with which key parameters could be established. The uncertainties were used, where possible, with the theoretical modelling to estimate the uncertainties in the fibre coating parameters that were achievable.

3.5. Theoretical modelling

The beam deflection method was modelled in more detail as the theory is less complex than for the scattering methods. No literature was found covering scattering from non-centred, non-circular fibre coatings. To develop the theory sufficiently for the same level of detail as the beam deflection method would require a substantial effort. However, some conclusions could be drawn from some relatively simple calculations.

4. Results from each technique

4.1. Beam deflection

4.1.1. Experimental Study

A cylindrical lens was chosen to give a beam waist of about $30\text{ }\mu\text{m}$. The fibre was scanned manually across the focussed laser beam and a moving broad bright line was observed on the screen. The centre of the bright line was seen to move in accordance with the predictions shown in the graph in figure 6 overleaf, which also identifies certain features referred to in the following text.

From measurements it was estimated that it is possible to locate the centre of the bright band with an uncertainty of less than 0.4 degrees. The centre may be more difficult to locate in the region near the feature labelled as 'Turning Point D' in figure 6, as the centre point will be confused by the wrapping around at this point. However, the features B and D remain clearly identifiable for a range of input offsets and it is estimated that their position may be located with an uncertainty of less than 0.1 degrees.

4.1.2. Theoretical study

The ray trace technique was modelled to determine the sensitivity of the technique to the fibre coating parameters. The model used the refractive indices and diameters for the coating layers given in reference 12. The values are given in table 1.

Region	Diameter	Refractive index
Air	-	1.0
Outer coating	$250\text{ }\mu\text{m}$	1.505
Inner coating	$200\text{ }\mu\text{m}$	1.486
Cladding	$125\text{ }\mu\text{m}$	1.458 46

Table 1. Parameters used to model the coated fibre

Using these values the variation of output ray angle with input ray offset is shown in figure 6.

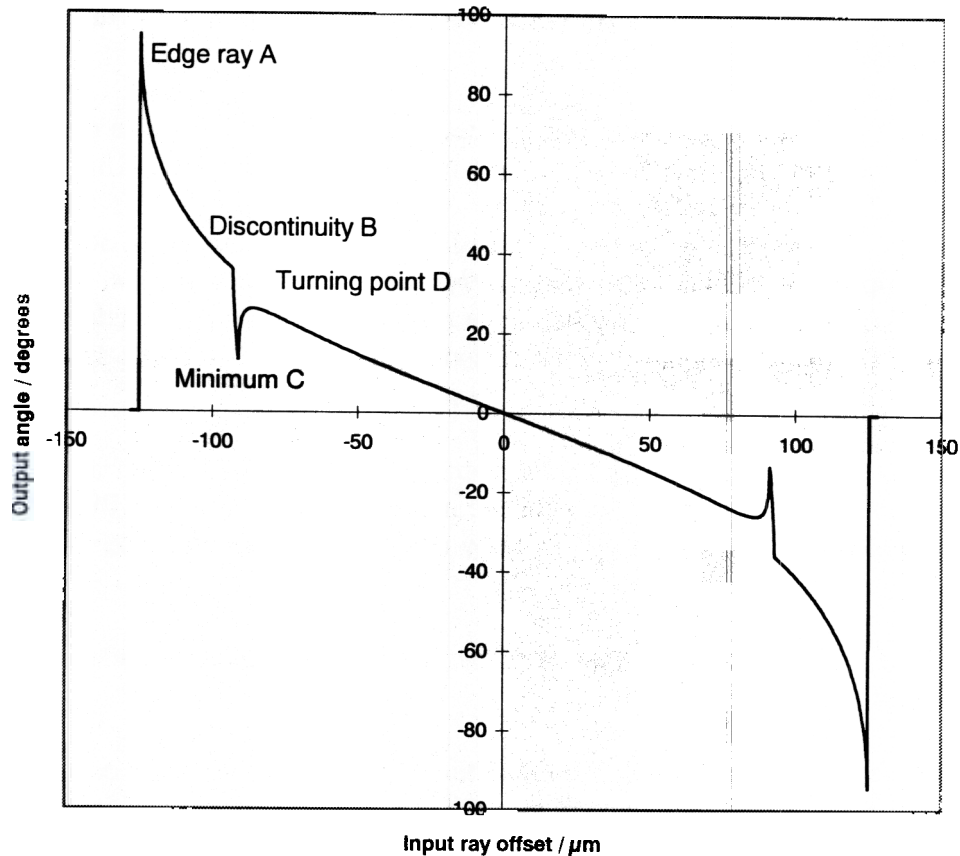


Figure 6

The features labelled 'edge ray A' and 'minimum C' are difficult to detect because of their relatively low intensity. The study has therefore not concentrated on the variation of the position of these features.

The features labelled 'discontinuity B' and 'turning point D' have significant amounts of light associated with them and so they are detectable. The ray that is at 'discontinuity B' is the ray that is tangential to the inner-coating/cladding boundary. Rays that are offset nearer the axis of the fibre undergo total internal reflection at the boundary and so have a very different emergent angle than those that miss the boundary.

If the fibre and its coating are circularly symmetric then the ray at 'turning point D' is the ray that is equally deviated at the two inner coating boundaries. This is not necessarily true for non-circularly symmetric fibres.

If each of the boundaries making up the coating are modelled as ellipses with offset centres then there are 14 unknown quantities to be determined:- 3 semi-major and semi-minor axes, two independent angular displacement of the ellipses and 2 independent pairs of co-ordinates describing the offset centres of the ellipses. If the input ray offsets and the output ray angles of B and D can be measured over a number of orientations of the fibre and approximated as sinusoidal variations of one and two periods per revolution (see later), then we have 23 measured quantities to fit the 14 unknowns. The system is then over-specified and so is, at first sight, solvable. However this depends on the input ray offset being measured with sufficient accuracy. The experimental trial

suggested that the output ray angle was measurable to about 0.4 degrees which corresponds to $1\text{ }\mu\text{m}$ of input ray offset around the feature B. Location of the output ray angle is therefore likely to limit the accuracy of the measurement.

Features B and D may be located with greater accuracy due to the finite size of the gaussian beam-waist effectively illuminating a range of input ray angles at the same time. This means that the dark region between B and D is visible for a range of input ray offsets. This allows more accurate determination of the output ray angles at positions B and D, but does not help to locate the corresponding input ray offsets more accurately. Measurements suggest that a measurement accuracy of the positions B and D may be of the order of 0.1 degrees or better. Determination by use of the B and D positions alone gives 17 measured quantities. This over-specifies the system of 14 unknowns.

It is possible that light passing through a multi-mode fibre core will be refracted into the angular range of the B and D features. If this happens the measurement sensitivity will be compromised and the measurements may be of no use. This study does not consider the effect of multi-mode fibre cores.

The sensitivity of the technique is investigated by varying each unknown independently around the initial values specified above.

The first quantities to be varied were the diameters of the outer and inner coatings. It was found that the input ray offset of the feature B did not vary significantly. The input ray offset of the feature D was also relatively insensitive. The change due to a difference of $2\text{ }\mu\text{m}$ of the outer coating diameter was found to be $0.2\text{ }\mu\text{m}$. Changes caused by variations in the inner coating diameter would be barely measurable.

The output ray angle of features B and D was also more sensitive to the change of the outer coating diameter than to changes to the inner coating diameter. A change of $2\text{ }\mu\text{m}$ in the outer coating diameter caused changes in the output ray angles of 1 degree and 0.8 degrees for the features B and D respectively.

A change of $2\text{ }\mu\text{m}$ in the inner coating diameter led to changes in the output ray angles of only 0.04 degrees and 0.03 degrees for the features B and D respectively. All changes of input ray offset and output ray angle were found to be linear to the first order.

The deflection of light by the coated fibre is also affected by the refractive indices of the coating and cladding of the fibre. As the cladding of the fibre is usually pure silica this was treated here as a known quantity. Variations of the outer cladding refractive index had very little influence on the input ray offset of feature B. They did, however, have a small effect on the input ray offset of feature D giving a $0.06\text{ }\mu\text{m}$ change for a change of 0.02 in refractive index.

The output ray angles show more significant changes with both features B and D moving by 0.3 degrees for the same change in outer coating refractive index.

The positions of features B and D are more sensitive to changes in the refractive index of the inner coating with the input ray offset changing between 1.5 and $2.5\text{ }\mu\text{m}$ for a 0.02 change in refractive index. The output ray angles change by between 2 and 3 degrees for the same change in refractive index.

The position of the features B and D were modelled with the cladding offset $1\text{ }\mu\text{m}$ from the centre of the coating, and with rotation of the fibre. With this offset the input ray offset for both features change by about 4 degrees with rotation of the fibre. These offsets should be easily measurable.

The variation of the output ray angles for both the D and B positions vary by about 2 degrees as the fibre is rotated. This change should be easily measurable.

The linearity of the changes of input ray offsets and output ray angle were also examined. The values were found to be linear with offset of the cladding to the first order. Together these suggest that the position of the cladding within the coating should be detectable to within $0.12\text{ }\mu\text{m}$.

The sensitivity to the offset of the inner coating centre relative to the outer coating centre was found to be less sensitive than the offset of the fibre cladding. Once again, the fibre was modelled with an offset of $1\text{ }\mu\text{m}$, this time applied to the centre of the inner-outer coating interface. The output angle changes by only 0.1 degrees with rotation of the fibre. The input ray offset changes of less than $0.1\text{ }\mu\text{m}$ are likely to be not detectable.

An offset of the inner coating centre may be distinguished from an offset of the fibre cladding by the different phase relations between the features from opposite sides of the fibre. For an offset fibre cladding, the positions on B and D from the two sides vary in phase with rotation of the fibre. For offset of the inner coating the relationship between the features of the two sides varies with no obvious phase relationship. Further investigation is required to find the precise phase relation.

The linearity of this measurement was also checked. As with offset of the fibre cladding, the changes of input ray offset and output ray angle are linear to the first order.

Examining the effect of outer coating non-circularity on the positions of features B and D showed that an outer coating non-circularity of 1 % led to variations in position of approximately $2\text{ }\mu\text{m}$ in the input ray offset and 1.6 degrees in the output rays. Non-circularity of the outer coating may be distinguished from offset by the number of periods of variation for a complete rotation of the fibre. An elliptical fibre will give two periods of variation for a complete rotation of the fibre compared to just one period given by a fibre with an offset fibre.

As with the case of the inner coating centre offset, the sensitivity of the technique to a non-circular inner coating is much smaller than the sensitivity to a non-circular outer coating. The changes in the input ray offset with rotation for an inner coating non-circularity of 1% are about $0.05\text{ }\mu\text{m}$ for both features B and D and so are likely not to be detectable.

Changes in the output ray angle for the two features are of the order of 0.1 degrees for the 1 % non-circularity of the inner coating. It is difficult to see how the technique will distinguish between changes in non-circularity of the inner outer coatings. Both effects give similar phase relationships between changes in the positions of features B and D on the opposite side of the fibre. The phase relationship between the changes of the input ray offset and the changes in the output ray angle for features B and D is also similar for non-circularity of the outer and inner coatings.

4.1.3. Beam deflection method summary.

By comparing the sensitivity of the measurable feature positions with changes in the parameters of the coating, the likely minimum uncertainties achievable using the beam deflection technique are given in the table below.

Coating parameter	Likely uncertainty
Outer coating diameter	0.22 μm
Inner coating diameter	6 μm
Outer coating RI	0.007
Inner coating RI	0.0008
Outer coating non-circularity	0.07 %
Inner coating non-circularity	1.6 %
Fibre cladding offset	0.12 μm
Inner cladding offset	2.6 μm

The estimated uncertainties depend on the validity of the estimates of the measurement uncertainties associated with the features in the previous section.

The sensitivity figures do not meet all of the requirements specified in the report “Fibre Coating Thickness and Geometry -The Results of a Survey of Industrial Users and Developers”.

4.2. Forward Scattering

4.2.1. Experimental Study

The scattering pattern observed in the forward direction has a fine structure made up of fringes of a period of the order 0.25 degrees, superimposed on a coarser structure of period of about 1.2 degrees. As the fibre is rotated the coarser structure and the finer structure move relative to each other. The finer fringes also change their period as the fibre is rotated. The structure of the pattern differs qualitatively when different fibres are observed.

The changes observed suggest that the method is sensitive to the geometry of the coated fibre.

4.2.2. Theoretical study

Developing the theory for this technique at a similar depth to that used for the ray trace method is a complex task which requires calculation of ray path differences, changes of intensity on reflection and integration over the many rays that will interfere in the far-field to produce the scatter pattern. However, some useful insight can be gained from a simple approach that does not calculate the full scatter pattern. By considering the optical path differences between rays passing through the fibre we can at least infer what changes to the fibre coating structure will be detectable to the forward scattering technique.

A sensitivity to phase of 10 degrees was assumed. This should give a significant change in either the height or position of a peak in intensity caused by two interfering rays. The diameter differences

of the outer and inner coatings that give this change in optical path are $0.03\ \mu\text{m}$ and $0.9\ \mu\text{m}$ respectively. The similarly the changes in refractive index that give the same change in optical path are 0.000 7 and 0.000 5.

Instead of considering the diametrical ray, a tangential ray gives a better sensitivity for changes in the inner coating diameter. A ray travelling tangential to the inner coating at a certain diameter will experience a change of optical path difference if the diameter is increased. Assuming no deviation takes place the detectable change in inner coating diameter is $0.002\ \mu\text{m}$. This treatment is not repeated for rays nearly tangential to the outer coating as they will be deviated by angle of about 90 degrees.

The sensitivities to changes in the diameter of the outer and inner coating non-circularity can be obtained from the changes in the diameters since the optical path of a diametrical ray will only depend on the diameter it is crossing. The detectable diameter differences can then be considered as the minimum detectable difference in the semi-major and semi-minor axes. This suggests detectable non-circularity of about 0.03 % and 0.9 % for the outer and inner coatings respectively. Using the value from the consideration of the tangential ray to the inner coating, the detectable non-circularity of the inner coating would be 0.002 %.

A factor limiting the beam deflection technique is the small number of measurands compared to the number of fibre coating parameters to be determined. The forward scattering technique is not constrained in this way since each scattering pattern contains a large amount of information and thus there is large amount of measurement redundancy.

The sensitivity to offset of the centre of the inner coating from the centre of the fibre cladding can be treated by considering the rays that, at one orientation, just miss a boundary and then calculating the extra optical path length for an un-deviated ray at a different orientation when the ray would have passed through that layer. The change in optical path suggests detectable offsets of $0.0005\ \mu\text{m}$ for both the inner coating and the fibre cladding.

4.2.3. Forward scattering method summary

By comparing the sensitivity of the measurable feature positions to changes in the parameters of the coating the likely best uncertainties achievable using the forward scattering technique are given in the table below.

Coating parameter	Likely uncertainty
Outer coating diameter	$0.03\ \mu\text{m}$
Inner coating diameter	$0.002\ \mu\text{m}$
Outer coating RI	0.0007
Inner coating RI	0.0005
Outer coating non-circularity	0.028 %
Inner coating non-circularity	0.002 %
Fibre cladding offset	$0.0005\ \mu\text{m}$
Inner cladding offset	$0.0005\ \mu\text{m}$

Table 3. Expected uncertainties from the forward scattering technique

All of these likely uncertainty figures are better than the requirements found in the report into the industrial requirements for these measurements.

4.3.Back-scatter

4.3.1. Experimental Study

As with forward scattering, the back-scattered light has a complex structure with fine and coarse fringes superimposed. The coarser structure period decreases with increasing angle and the relative positions of coarse and fine features change with rotation. The structure of the pattern differs qualitatively when different fibres are observed.

The changes observed suggest that the method is sensitive to the geometry of the fibre and its coating.

4.3.2. Theoretical study

The back-scatter pattern is formed in a similar manner to the forward scattered pattern but here some light travelling through the fibre is reflected internally. In the far-field the reflected light interferes with light reflected from the outside of the coating to produce the complex interference pattern. In this sense it is a “double pass” technique as the light has travelled twice across the fibre, so we can expect it to have a sensitivity twice that of the forward scatter technique. This suggests that the technique should be able to detect changes in the outside diameter of a coated fibre of about $0.015\text{ }\mu\text{m}$. This compares well with the uncertainties found in the measurements of fibre cladding diameter carried out previously by NPL, which enabled a fibre cladding diameter to be measured with an uncertainty of the order of $0.02\text{ }\mu\text{m}$. Note that, in the case of bare fibres, scatter patterns are repeated with a period of half the wavelength of the illuminated light and so the approximate diameter must be known in advance to this accuracy. In practice, this was easy to achieve. However, the optical properties of bare silica fibres are much better than those of the coatings that will be birefringent and have structured surfaces.

As with the forward scattering technique, there is no constraint imposed by a limited number of measurands compared with the number of fibre coating parameters that need to be determined. Each scattering pattern contains a large amount of information and so there is large amount of measurement redundancy here too.

4.3.3. Back-scatter method summary

Because the light scattered back in the direction of the source has traversed the fibre twice, the sensitivity of this method is potentially a factor of two better than the forward scattered method. As stated in section 4.2.3, the estimated likely uncertainties associated with the forward scatter method are better than the requirements identified in the previous study on industrial requirements. However, the issue of the optical inhomogeneity in the coating layers, and its effect on the observed back-scatter pattern, was not included in this study.

5. Traceability of the methods and other issues

All three of these techniques require the measurement of changes of intensity of light at differing angles emerging from the fibre. If the linearity of the detection system can be established then traceable measurement of optical power is not required.

The wavelength of the light used is important for all three methods but, using laser sources, it is easy to establish traceability.

For the two scattering techniques, the traceability of the angular measurement of the scattered rays is the main concern. This is easy to establish using traceable angle standards. For example, prisms could be used to give well defined angular reflections or deviations of the incoming beam. Goniometric techniques can be used to make the angular measurements to the highest accuracy but these are likely to be time consuming, an important consideration for a practicable, affordable measurement service.

It is likely to be more practical to use a CCD camera array for making the measurements. Accuracy is limited by the ability to calibrate the measurement of angle at the sample from the location on the CCD array. However, if this can be overcome, a CCD-based system makes the measurement amenable to automation, reducing the cost of making the measurements.

Angular rotation of the fibre between measurements is also important, but the required precision of this measurement of the orientation of the sample is low.

Both scattering methods have the potential to meet the present industrial requirements for coating measurements, with back-scatter likely to have the greater sensitivity of the two.

Development of theory to derive fibre coating parameters from measured scattered light patterns is required. The theory for calculating refractive index profiles from back-scattered data has been developed for circularly symmetric fibres but no such framework was found for the case of non-circularly symmetric fibres. The computation of the scattered light pattern from a fibre is conceptually straight-forward. However, the inverse problem, working backwards from a set of scatter patterns to a fibre model is much more difficult, perhaps requiring a man year of theoretical work. In the NPL study of measurements of bare fibres, the method used visual matching of pre-calculated patterns with the measured profile. This required knowing the diameter of the fibre to within about one half wavelength. A scheme of this kind would be impracticable for asymmetric fibre coatings.

The beam deflection method has similar traceability considerations as the scattering methods for the angular measurements. In addition, the offset of the beam entering the fibre must also be measured. This is a length measurement and if the fibre is scanned rather than the spot, the fibre position can easily be measured by an interferometer. If the spot is scanned then its movement can be traceably calibrated by scanning a wire or chrome mask of known width across a detector array with known element spacing.

However, the ray trace method does not have the potential to meet the present industrial requirements for coating measurements.

6. Cost estimates

It is estimated that the cost of developing a system for measuring the coating parameters by the either scattering method would be £130k. This includes equipment, 1 year of theoretical development and 3-6 months experimental development work.

7. Conclusions

Three methods for measuring the coating parameters for optical fibres have been selected and examined experimentally and theoretically.

The ray trace method was found to have insufficient sensitivity to meet the industrial measurement requirements found in the report "Fibre Coating Thickness and Geometry - The Results of a Survey of Industrial Users and Developers".

The forward and back-scatter techniques were found to have sufficient sensitivity to meet the requirements in the above report. The back scatter technique is likely to be the more sensitive of the two scattering techniques.

Traceability issues for the techniques have been considered. It is believed that traceability of measurements can be achieved.

However, the development of the techniques will be theoretically intensive. There was about a man years effort required to develop the theory for use on asymmetric fibre coatings. The development of the instrumentation and establishing traceability will require a further 6 man-months effort.

The effort required to develop a traceable measurement system is probably not justified considering the current and medium-term future industrial demand.

8. Appendix A - Parameter Definitions

In this section the geometrical fibre parameters of interest are described and their generally accepted definitions given.

8.1 Outer diameter

This is the diameter of the outermost coating of the fibre. All fibres have show a degree of non-circularity in their coatings. Reference 2 defines outer diameter (OD) as

$$OD = \frac{MaxOD + MinOD}{2}$$

where MaxOD and MinOD are the maximum and minimum measured outer diameters of the fibre coating.

Another definition, outlined in reference 3, allows the fitting of an ellipse to the shape of the coating. This leads to the definition

$$OD = A + B$$

where A and B are the semi-major and semi-minor axes of the ellipse fitted to the data. This is equivalent to the previous definition if the coating has the form of an ellipse.

Other fitting techniques are possible

8.2 Non-circularity

The deviation from circularity may be described as the non-circularity (NC). Reference 2 defines non-circularity (NC) as

$$NC = \left[\frac{2(MaxOD - MinOD)}{MaxOD + MinOD} \right] \cdot 100\%$$

Most fibres require the circularity of the coatings to be good, though some types of fibre (for example polarisation maintaining fibres) may benefit from a non-circular coating.

The method outlined in reference 3 gives the fitted ellipse definition of the non-circularity as

$$NC = 200 \cdot \frac{A - B}{OD} \%$$

Once again this is equivalent to the previous definition if the coating has the form of an ellipse.

8.3 Concentricity

This parameter describes the alignment of the centre of the coating with the centre of either the fibre core or the centre of the cladding of the fibre. Alignment of cores in connectors is essential for ensuring efficient coupling of light from one fibre to the next.

Concentricity is defined as the distance between the centre of the coating outer surface and the centre of the cladding or core.

8.4 Coating wall thickness

The coating wall thickness is as it is described, the radial thickness of the individual coating layers. This will vary around the circumference of a fibre if the fibre cladding or the fibre coating are non-circular or non-concentric.

8.5 Actual shape

This refers to what the shape of the fibre really is rather than the use of a descriptor such as an ellipse or circle. Unlike the cladding of a fibre, the outer coating shape is often very irregular. Ridges and grooves in the coating surface can limit the ability of a single number to describe the diameter of a coating layer.

8.6 Inner diameter

Many fibres have more than one coating. The inner coating diameters refer to the diameters of the layers between the cladding and outer coating. Such layers can be described in the same way as the outer diameter.

8.7 Refractive index of coatings

The refractive index, n , of a material is defined in the following equation

$$n = \frac{v_{vac}}{v_{material}}$$

where v_{vac} is the speed of light in a vacuum and $v_{material}$ is the speed of light in that material.

The refractive index properties of the fibre coating may be tailored to enhance the removal of whispering gallery modes from the guiding core of the fibre.

9. Appendix B - References

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