THE PRODUCTION AND TRANSMISSION CHARACTERISTICS OF LOW-LOSS OPTICAL FIBRE WAVEGUIDES

DAVID N. PAYNE

A thesis submitted for the degree of
Doctor of Philosophy
at the University of Southampton

Department of Electronics
August 1976

CONTENTS

UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF SCIENCE
ELECTRONICS

Doctor of Philosophy

THE PRODUCTION AND TRANSMISSION CHARACTERISTICS OF LOW-LOSS OPTICAL FIBRE WAVEGUIDES

by David Neil Payne

A study is made of both the manufacture and the characteristics of low-loss cladded optical fibres for use in the telecommunications network. A description is given of the evolution of the fibre drawing technology and of the development of several types of low-loss fibre. These include fibres having core materials composed of commercially-available compound glasses, a specially-produced high-purity lead glass, an organic liquid and a vapour-deposited phosphosilicate glass. Attenuation figures range from 150dB/km to 1dB/km respectively.

The propagation characteristics of the fibres are considered and it is shown that partial excitation of multimode step-index waveguides is both advantageous and practicable. Particular emphasis is placed on an investigation of the effect on pulse dispersion of preferential mode filtering and mode conversion.

The thesis includes three new measurement techniques for the characterisation of optical fibres. The first is a method for the determination of the material dispersion in phosphosilicate glass over a wide wavelength range. Resulting from the measurement it is shown that a wavelength region exists in phosphosilicate fibres where the material dispersion is zero and the loss is small. It is suggested that operation at this wavelength would be preferable to that currently envisaged for optical communications.

The second is a means for evaluating the waveguide parameters of a single-mode fibre. The method relies on observations of the far-field radiation pattern and permits the simultaneous measurement of both core diameter and refractive-index difference.

The third is a near-field scanning technique for assessment of the profile of graded-index fibres. The near-field intensity distribution of the fibre is plotted and a correction applied to yield the refractive index profile. A study of leaky modes in graded-index fibres furnishes the required correction.

ACKNOWLEDGEMENTS

I am indebted to Professor W. A. Gambling for his help and guidance throughout this work. In addition to his substantial contribution to the research, he has provided encouragement, advice and friendship over the years, the value of which is difficult to overstate. His support was particularly appreciated during a disastrous period early in the work, when all research records were destroyed in the fire which consumed our offices. I would also like to acknowledge with gratitude his tireless unscrambling and translation of my tortuously constructed sentences into a publishable form.

I am particularly grateful to all those colleagues, past and present, who have contributed to the group research. The intellectual stimulation and companionship they have provided is immeasurable. I hesitate to single out individual workers from the many, but this thesis would not be complete without mention of Dr. H. Matsumura, Dr. M. J. Adams and Mr.F.M.E.Sladen, who have co-authored so many of the publications.

It is inconceivable that the work would have even started without the help of Mr. R. Came, of the mechanical workshop. He has the uncanny ability to convert my half-formed ideas and an incomprehensible sketch into a precision-dowelled, stainless-steel distillation of my requirement. His scorn at subsequent modifications has convinced me of the wisdom of clear experimental planning.

Mrs. Jan Ditchfield has contributed both to the thesis and to the publications by her painstaking preparation of the manuscripts. There have been times when her assistance has stopped only just short of actually writing the text. In addition, her wrath has taught me that two drafts of a manuscript are sufficient, even for the most meticulous of authors.

Lastly, I would like to acknowledge the substantial assistance of my wife, Linda, in the completion of the thesis. Her departure for the U.S.A. for four months and the vacuum this has created has finally persuaded me to write this long-overdue dissertation.

Notes on the text:

i) References are numbered consecutively and listed at the end of each chapter.

ii) Relevant publications are bound at the end of each chapter. As an aid to the reader the appropriate publication number is given in brackets after the title of the subsection in which it is introduced. Publications within each chapter are numbered consecutively and are preceded by the letter P and the chapter number.

iii) A publications index giving the thesis numbering may be found after the conclusions.

iv) Figures are given at the end of each chapter.

v) Page numbering is confined to the text only. The page numbers found on the publications are those of the source journal, and should be ignored.

I N T R O D U C T I O N

Fibre optical communications and the allied field of optical electronics is expected to have a technological impact similar to those of the transistor and, more recently, the integrated circuit. The work reported in this thesis charts the progress of the new technology, from shortly after its speculative inception with the classic paper of Kao and Hockham[1], to its present prominence. The publications which are included in the text cover the period August 1971 to August 1976, a period which has seen the growth of published work from an unsteady trickle to an overwhelming avalanche. The present work, therefore, has both a scientific and a historical interest in that it traces the emergence of what is undoubtedly one of the major technologies of the 1970's.

If it is not too immodest a claim, the work presented here has played a not inconsiderable part in the advancement of fibre communications. Milestones which may be found in the text, but which are particularly worthy of recall are:-

1) The first demonstration of precision fibre drawing and the achievement of fibre losses similar to those of the bulk glass (1970).
2) The development of a novel, low-loss liquid-core fibre based on a high-loss, compound-glass cladding filled with hexachloro-buta-1,3-diene. The fibre for some time claimed the lowest loss recorded and remains the lowest loss liquid-core fibre ever produced (1972).
3) The realisation that partial excitation can lead to high bandwidth in multimode step-index fibre waveguides. The first theory of pulse dispersion in multimode fibres was evolved to describe the effect (1972).
4) The observation and characterisation of 'microbending' in optical fibres. The effect is now recognised as having critical importance in the cabling of optical fibres (1972).
5) The first public demonstration by the British Broadcasting Corporation of a live colour television programme transmitted over 1.25km of liquid-core optical fibre. The quality of the signal broadcast and received throughout the United Kingdom was indistinguishable from a normal transmission (January 1973).

6) The development of the homogeneous chemical vapour deposition technique for fibre production. This was accompanied by the discovery of a new material, phosphosilicate glass, for the fabrication of ultra-low-loss, silica-based waveguides. The technique of fibre fabrication has subsequently been adopted worldwide, while the phosphosilicate material has since been used with outstanding success by both Japanese and American laboratories (1974).
7) A proposal to shift the operational wavelength for a fibre communication system from the present-day 0.9μm, to 1.3μm. With the discovery of the phosphosilicate fibre came the demonstration of both the advantages in terms of channel bandwidth and the technical feasibility of the change. The impact of this radical proposal has yet to be fully felt, but existing work on phosphosilicate fibres in other laboratories confirms that a major change of emphasis may well result in the near future (1975).
8) The discovery of three techniques for the characterisation of step-index, graded-index and single-mode fibres. These enable the determination of
   i) the chromatic dispersion of the waveguide material over a wide wavelength range;
   ii) the refractive-index profile of graded-index fibres from a near-field scan;
   iii) the simultaneous measurement of the propagation parameters of a single-mode fibre from a single observation of the far-field intensity distribution.

The thesis is divided into three Sections, covering fibre fabrication, optical propagation studies and graded-index fibres. Although there is considerable overlap between the Sections, the work within each is presented in chronological order. The Sections are inter-related in that the first Section details the manufacture of a particular fibre, while the remaining two are concerned with its evaluation.

Section I describes fibre fabrication. It begins with the production of fibres having a loss of 1dB per metre and traces the progress to the present day attenuation figure of 1dB per kilometre. In order of attenuation, the investigation covers (a) fibres made from commercial compound glasses, (b) fibres made from high-purity preforms provided by Sheffield University, (c) liquid-core fibres and (d) phosphosilicate fibres made by homogeneous chemical vapour deposition.

Section II is devoted to an investigation of the propagation characteristics of the various fibres described in Section I. A simple ray model is developed to account for the observed dependence of pulse dispersion on launching conditions. Comparison with experiment reveals good agreement for all but the lowest-order modes. Departures from the simple theory caused by mode coupling and differential modal attenuation are investigated, leading to a theory modified to include the latter effect. A comprehensive study of mode coupling follows, culminating in the development of a method for measuring the degree of coupling which exists in a step-index waveguide. It is shown that the intrinsic mode scattering present in our fibres is negligible; the small amount normally found is induced by external stress. The Section ends with a description of the most recent work on single-mode fibres.

Finally, Section III describes a simple and rapid method for determining the refractive-index profile of an optical fibre by observation of the near-field intensity distribution. It is shown that in many cases the presence of tunnelling leaky modes is unavoidable and that these cause an error in the measurement. A study of leaky modes shows that their existence accounts for several other inconsistencies previously encountered in measurements on graded-index fibres. A correction factor is developed which permits accurate observations to be made.

The thesis consists of both explanatory text and published papers. The text is intended to provide a review of the published work and to relate it to more recent results. The appropriate publications are collected at the end of each chapter and it is suggested that they are read in conjunction with the text, rather than after it.

References

1. Kao, K.C. and Hockham, G.A.:'Dielectric-fibre surface waveguides for optical frequencies', Proc. IEE, 1966, 113 pp 1151-1158.

SECTION I

FIBRE PRODUCTION

CHAPTER 1

THE DEVELOPMENT OF A FIBRE-FABRICATION FACILITY

1.1 The Fibre-Drawing Machine (P1.2, P3.5)

In early 1968, at the commencement of the work to be described, very little expertise was available in optical fibre production, much less in production of optical fibres for communications purposes. As in most budding technologies, the manufacturing process was shrouded in mystery, and was generally thought to be an art rather than a science. Thus it was accepted that optical glasses which were known to have bulk losses of around 100dB/km would inevitably give an attenuation of 1000dB/km when pulled into a cladded-glass lightguide. It was clear, therefore, that if optical-fibre communication was to become a reality a careful, investigative study of the fibre drawing process would be necessary in order to determine the origin of this, so-called, 'excess loss'. It is instructive to note that despite the almost unbelievable attenuation figure of 0.47dB/km[1] now achieved in communication lightguides, the attenuation of commercially-available fibre bundles has remained almost unchanged at 1dB/km; this loss is apparently acceptable for most simple 'light pipe' applications.

The initial objective, therefore, was to design and construct a precision fibre-drawing machine specifically for research into the fibre fabrication process. Additional work was initiated[2] to determine the losses of commercially-available bulk glasses, and it was hoped eventually to produce fibres of a similar attenuation, that is in the region of 100dB/km. Although it was accepted that this figure was too high for optical communications to be a viable proposition, it was clear that its achievement would provide impetus for the development of glass of higher purity. In retrospect the objective of 100dB/km appears trivial, however the excitement generated by our eventual achievement of first 400dB/km and then 150dB/km is an indication of the magnitude of the task at that time.

Faced with a total lack of expertise in both glass technology and fibre optics, it was decided that the only logical design strategy for the fibre-drawing machine was one of precision. For example, the accuracy that would be required for the fibre pulling speed was unknown, so it was decided to make it as constant as could reasonably be achieved. This policy was followed for all major components of the machine and some care was taken to ensure stability and vibration-free operation. The rod and tube[3] method of manufacture was chosen after some consideration of the alternative concentric crucible[4] method. The decision was made on the basis of cost, simplicity and versatility. The concentric crucible approach whereby molten glass is drawn from two coaxial nozzles has several attractions, not least of which is its continuous production capability; however the merits of our decision will become apparent in the chapter on silica-based fibres. A brief description of the machine follows.

As shown in Fig.1.1, the machine consists of two vertical bars to which all units are clamped, enabling removal or adjustment of any unit. The cleaned and concentrically-assembled rod and tube are clamped in a gimballed chuck which, together with the centering iris diaphragm at the top of the furnace, allows for slight bends in the preform. The assembly is mounted on a crosshead and smoothly lowered into the furnace at a predetermined rate by a vertically-mounted lead screw. The feed rate is adjustable both by means of a system of belts and pulleys, and by an electronic speed controller. The glass softens within the furnace and tapers into a filament whose diameter is a function of the ratio of the preform feed rate to the fibre-drawing speed. The fibre passes over a graphite guide onto an accurately-machined speed-controlled aluminium drum at the base of the machine. The drum is traversed slowly sideways to ensure that the fibre is wound in a mono-layer, one layer having a length of ∿3km. The pulling speed is variable between 0 and 10 metres per second. Means is provided to electronically lock the pulling speed and feed rate together, thereby causing the rates to vary in a predetermined ratio and the fibre diameter to remain substantially unchanged as the pulling speed is increased. The stability of both speeds is better than 0.1%.

It was appreciated from the outset that the degree of fluctuation in fibre diameter would be largely determined by the accuracy with which the furnace temperature could be controlled. The furnace construction is sketched in Fig.1.3. The design was chosen to have a low thermal inertia to allow rapid temperature changes to be made. The heating element is based on a spiralcut alumina tube into which a multi-tapped platinum wire element is cemented. Each of the taps is brought out to a terminal board so that experiments can be made to determine the optimum length of the hot zone. Other novel features are the use of iris diaphragms at both input and output ends of the furnace, as well as a thermocouple whose position may be adjusted within the hot zone so as to monitor and control a given region of the softened preform. The upper iris diaphragm has the dual role of centering the preform within the furnace and of excluding convection air currents. The presence of turbulent air flow through the furnace was found to be a major cause of fibre diameter fluctuations.

Further details of the fibre-drawing machine may be found in publication P1.2 and P3.5. A measure of the success of the design may be gained by noting that both machine and furnace are today operating substantially unchanged from the original concept. The versatility of the machine has been shown by the production of various fibres including liquid-core, single-material and silica-based waveguides. The latter has required the addition of a graphite furnace (publication P3.1) in order to achieve the necessary pulling temperature of 2000^{o}C. The design of this furnace has drawn heavily on the experience gained with the earlier experimental furnace.

A further indication of the performance of the machine is given by the adoption of the design by two major industrial concerns, one in the United Kingdom and one in North America. Moreover, it is gratifying to have been consulted by long-established glass manufacturers on the production of precision glass fibres for use in mechanical engineering.

1.2 Fibres Produced from Optical Glasses (P1.1, P1.2)

After the construction of the fibre-drawing machine, a systematic investigation was made of the origins of the high fibre losses which had been previously observed. It had now been established[2] that the lowest-loss commercial glasses available were Schott F7, a lead-based optical glass, for the core and Chance-Pilkington ME1 tubing for the cladding. Fortunately,this combination proved compatible both thermally and mechanically, and so it was used exclusively. A scanning-electron micrograph of a typical fibre is shown in Fig.1.2.

Publications P1.1 and P1.2 at the end of this chapter give details of the results obtained. We were able to show that the high losses associated with commercial fibres were largely a result of core/cladding interface imperfections and that with care a loss of 300dB/km could be routinely achieved. This was brought about by:-

a) Elimination of impurities on the surfaces of both rod and tube by a cleaning procedure which involved degreasing and hydrofluoric acid etching, followed by vapour drying in iso-propyl alcohol.

b) Degassing of the surfaces at high temperature so as to avoid interfacial bubble inclusions.

c) The evolution of a novel technique which allowed fire-polishing of the surfaces before they fused. This was accomplished by using a loose-fitting 5mm F7 rod centered within a 12mm bore ME1 tube. The core and cladding then taper separately and fusion between the two glasses is delayed to a point where the preform has virtually attenuated into a fibre. Both surfaces are then smoothed by viscous flow induced by surface-tension forces.

The final elimination of the excess fibre loss was achieved by heat treatment of the fibre, as described in detail in the following publications P1.1 and P1.2 (note that the captions to figs 2 and 3 are reversed in P1.1). After extensive trials had failed to reduce the fibre loss below 300dB/km, it was reasoned that the only remaining possibility lay in the difference in thermal history of the core glass in bulk and in fibre form. The exact mechanism involved in the dramatic reduction to 150dB/km which followed is not fully understood, although a tentative explanation is given in the publications. It is interesting to observe however that recently[5] it has been further recognised that the properties of a glass in its chilled fibre state may be radically different from those in its annealed bulk condition.

1.3 Fibres Produced from High-purity Compound Glass (P1.2)

We had succeeded in developing a fibre-drawing technique which did not result in an increase in attenuation over that observed in the bulk glass. This was put to the test when preforms of high-purity glass became available from the University of Sheffield[6]. The preforms were in the form of a high-lead-content core glass sheathed with a borosilicate composition. The glasses were chosen to provide a large refractive index difference and thus a high numerical aperture. The drawing of these preforms into fibre proved a severe test of the fibre drawing machine capabilities as they were of small diameter (approximately 2mm), were often far from straight, and had a low softening point. However 500 metres of good quality fibre were obtained from each preform, and a typical attenuation result is given in P1.2.

Unfortunately heat treatment of those fibres did not produce as dramatic a reduction in attenuation as had been experienced with the F7/ME1 combination. Nevertheless, at the culmination of the cooperative programme a very acceptable loss figure of 35dB/km had been achieved at a wavelength of 850nm, as shown in Fig.1.4. The insistence on a high fibre numerical aperture by the contractors supporting the work without doubt prevented further improvements in the fibre attenuation. A high numerical aperture (0.68) requires a core glass having a large refractive index. High-lead content (40m/o) glasses must be used and these have increased intrinsic absorption and scattering losses. It may be observed that present-day ultra-low-loss fibres all have a numerical aperture lower than 0.2. The attenuation of 35dB/km represents the lowest reported for a fibre having so high a numerical aperture.

1.4 Discussion

The value of the precision fibre drawing machine and the techniques learned in these early experiments cannot be overstated. They form the groundwork on which all our subsequent activities in fibre technology have been based. The equipment has been extensively used in the later development of both liquid-core and silica fibres. Furthermore, the understanding of the surface smoothing which occurs during fibre drawing and the fundamental stability of the fibre drawing process led to a greater insight into the accompanying work on optical propagation. It is, after all, the viscous nature of softened glass and the ease with which it can be drawn into a smooth fibre devoid of all rapid variations along its length which is the raison d'etre of optical communications. Fortunately an early paper[7] which implied that fibre attenuation would be limited by the existence of such imperfections did not prove too discouraging!

Although not described here, the construction of the fibre-drawing machine was accompanied by the development of measurement techniques for the determination of fibre spectral attenuation, numerical aperture, diameter and scatter loss.

References

1. Horiguchi, M. and Osanai, H.:'Spectral losses of low-OH-content optical fibres', Electron. Lett., 1976, 12, pp 310-312.

2. Laybourn, P.J.R., Gambling, W.A. and Jones, D.T.:'Measurement of attenuation in low-loss optical glass', J. Opto-Electron., 1971, 3, pp 137-144.

3. Kapany, N.S.:'Fiber Optics', Chapter 5, Academic Press, New York, 1967.

4. Beales, K.J., Midwinter, J.E., Newns, G.R. and Day, C.R.: 'Materials and fibre for optical transmission systems', The Post Office Electrical Engineers' Journal, 1974, 67, pp 80-87.

5. Wemple, S.H., Pinnow, D.A., Rich, T.C., Jaeger, R.E. and Van Uitert, L.G.:'The binary SiO_2-B_2O_3 glass system: Refractive index behaviour and energy gap considerations', J. Appl. Phys., 1973, 44, pp 5432-5437.

6. Scott, B. and Rawson, H.:'Preparation of low-loss glasses for optical fibre communication systems', J. Opto-Electron., 1973, 5, pp 285-288.

7. Marcuse, D.:'Mode conversion caused by surface imperfections of a dielectric slab waveguide', Bell Syst. Tech. J., 1969, 48, pp 3187-3215.

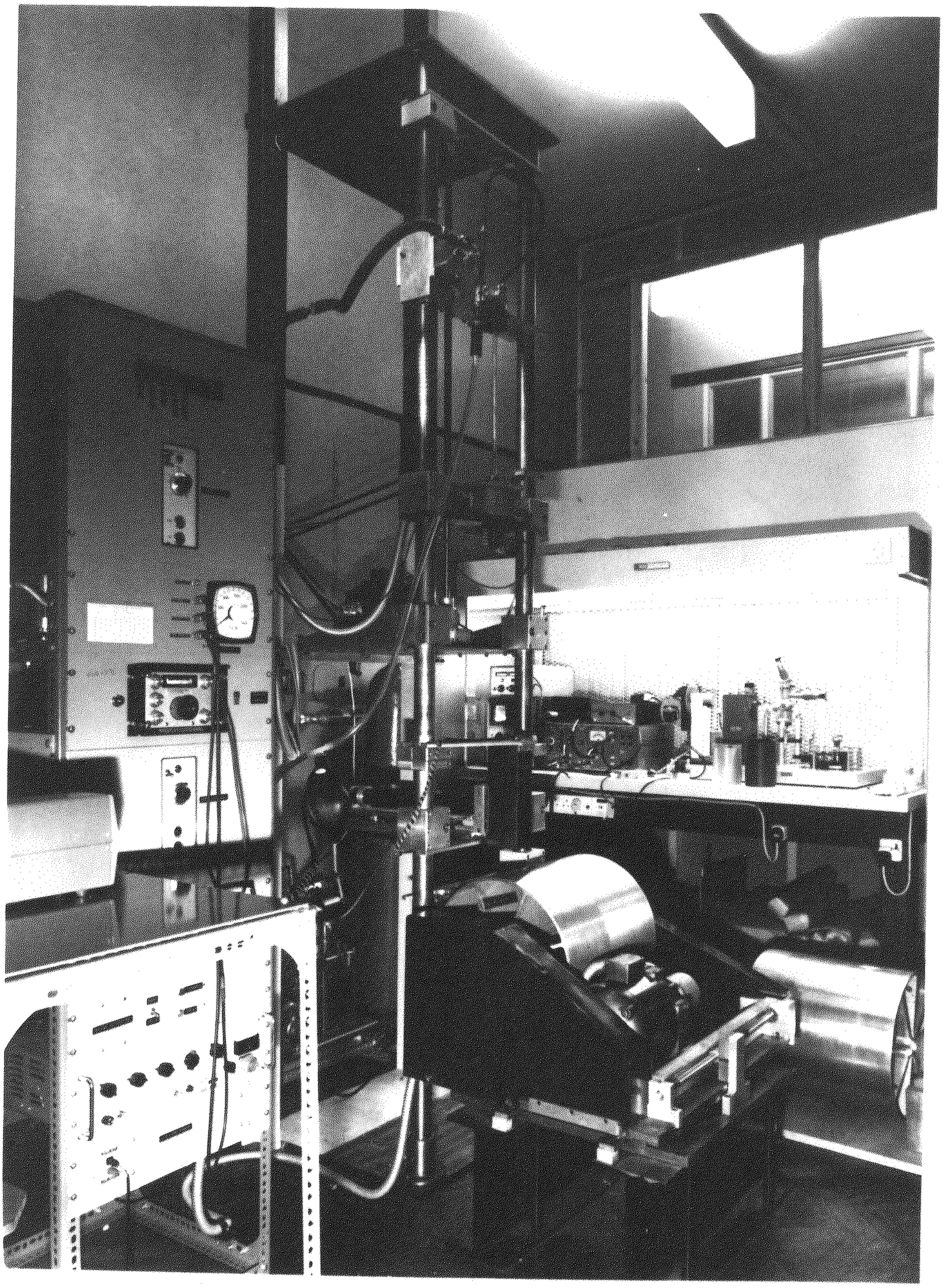


FIG.1.1 THE FIBRE DRAWING MACHINE

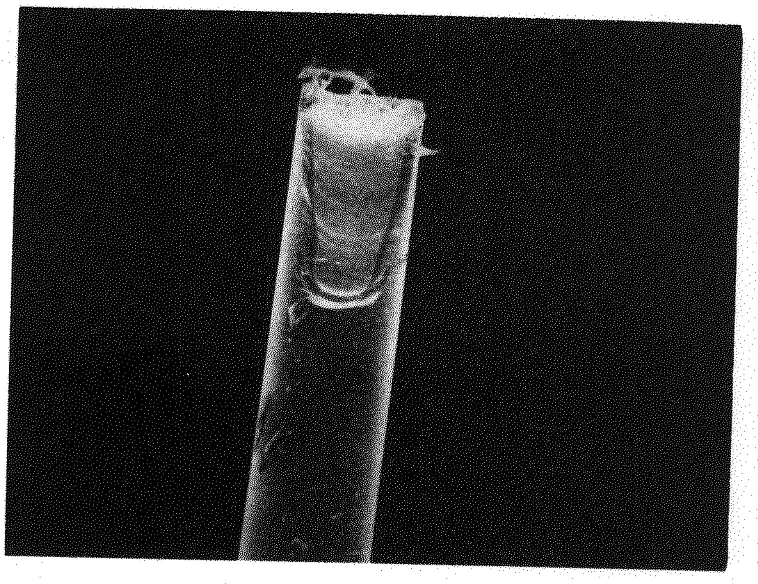


FIG.1.2 BROKEN END OF ME1/F7 FIBRE

DIAMETER 95μM

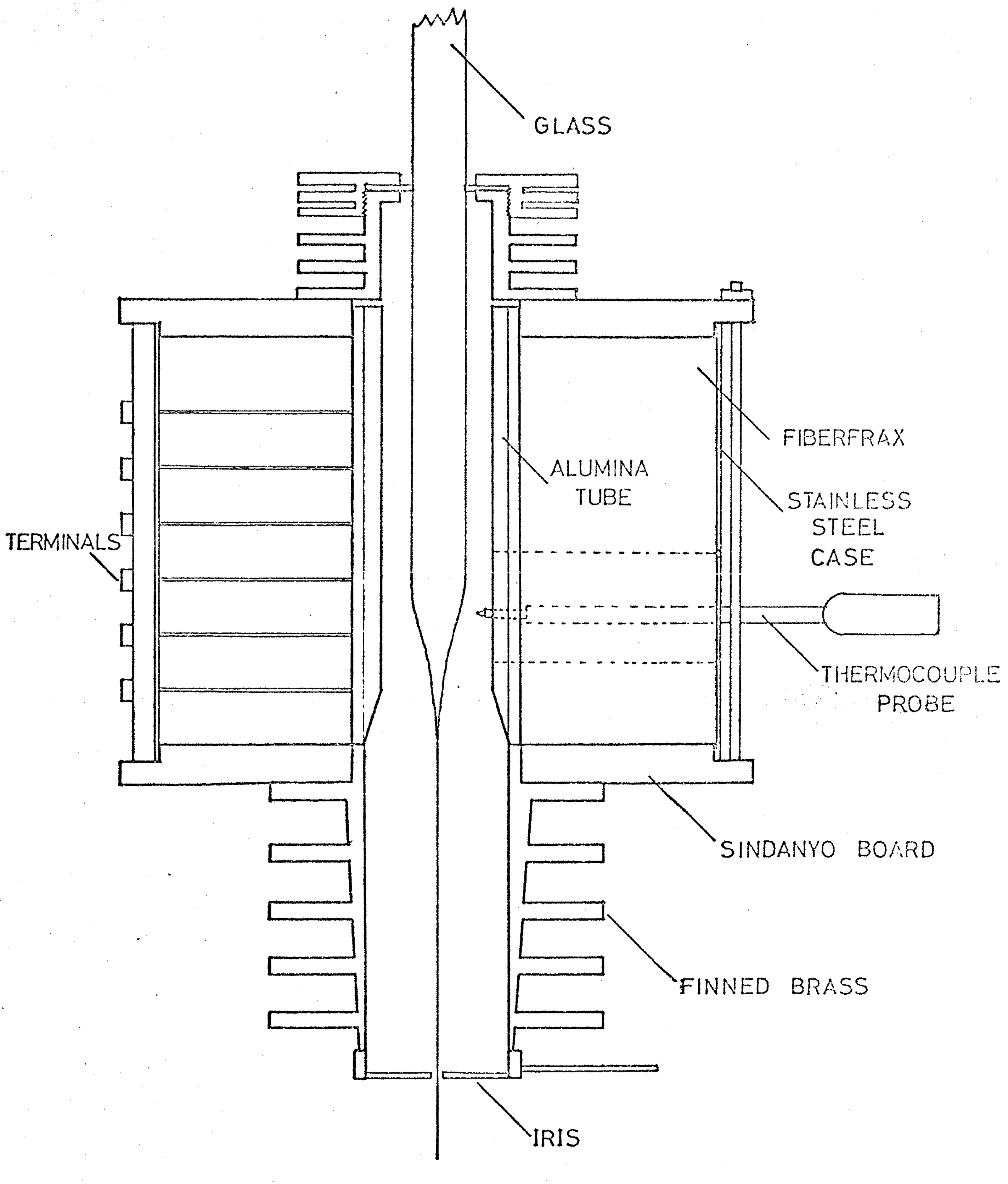


FIG.1.3 THE PLATINUM-WOUND FURNACE

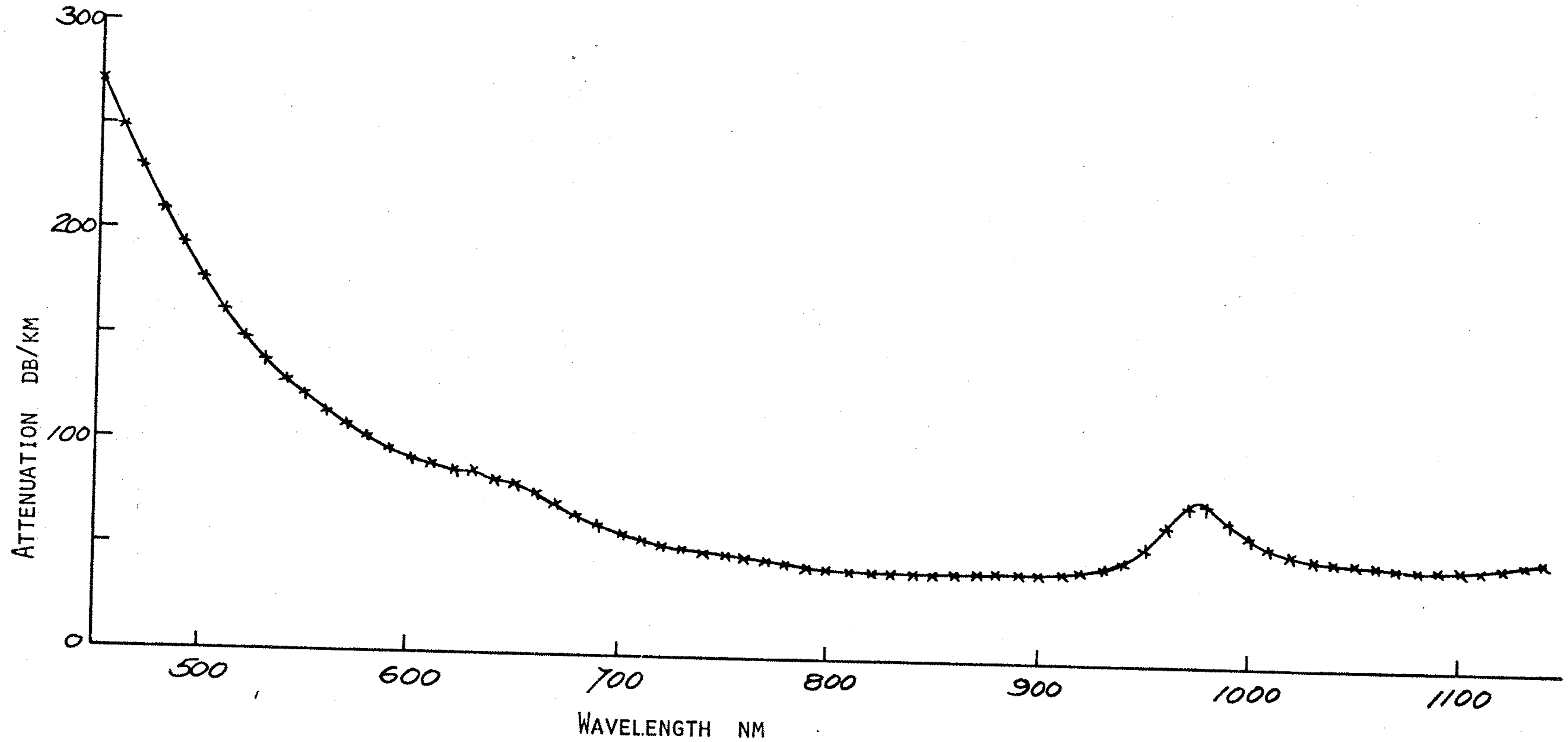


FIG.1.4 SPECTRAL ATTENUATION OF FIBRE DRAWN FROM PREFORMS SUPPLIED BY SHEFFIELD UNIVERSITY

PUBLICATION P1.1

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

F.F.Y Wang, J.P.Dakin, D.N. Payne, W.A. Gambling (1974) "Relaxation process in glasses as shown by optical attunuation experiments." Journal of Non-Crystalline Solids, Vol.14 Issue: 1. Pp.48-53

PUBLICATION P1.2

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

https://doi.org/10.1007/bf02057129

CHAPTER 2

THE DEVELOPMENT OF A LIQUID-CORE FIBRE

2.1 Glass-cladded Fibres based on Hexachlorobuta-1,3-diene (2.1)

Once the fibre-drawing process had been improved, it fast became obvious that the bulk attenuation of the material used for the core of the fibre was the limiting factor in the achievement of lower attenuation. Since the possibilities of commercial glasses had been exhausted and the effort at Sheffield University was hamstrung by the contractors insistence on high numerical aperture, there seemed little prospect for further progress. It was at this time that the use of a liquid core was suggested at the CSIRO in Australia[1] and at Bell Telephone Laboratories[2]. They claimed the then lowest recorded attenuation of 15dB/km at 1.06μm with a fibre consisting of a pure silica fibre tube filled with tetrachloroethylene.

Clearly liquid-core fibres provided a means of circumventing the problem of obtaining a glass core of adequate purity, and so it was decided to investigate their properties. Expertise in the production of fibre capillary had already been gained during the experiments on delayed closure of the F7/ME1 core/cladding combination. However early trials at Southampton on the filling of fibres made from either ME1 or Pyrex with tetrachloroethylene quickly indicated that the index difference between core and cladding was inadequate. A low numerical aperture results in a relatively large proportion of optical power propagating in the cladding. Thus the high optical attenuation of the cladding material was reflected in the measured overall loss and a fibre attenuation no better than 50dB/km could be obtained. (An experimental and theoretical study of this effect may be found in publications P5.1 and P5.3.) The previously-reported silica-cladded fibre had not suffered from this problem, both because the index difference is greater, and because silica has a relatively low loss. We could not produce silica fibres at that time, as the maximum temperature of the fibre-drawing furnace was too low to permit silica drawing. An alternative approach was to find a liquid having a higher refractive index than tetrachloroethylene.

Unfortunately, as with glasses, it transpires that to a certain degree the optical attenuation of a liquid increases with its refractive index. Since the refractive index and the proximity and intensity of the ultraviolet electronic absorption bands are related through the Kramers-Kronig relationship, this is perhaps not altogether surprising. In addition , it is found that the presence of a hydrogen atom within the molecular structure of the liquid produces an intense absorption band at a wavelength of 3.5μm. Hydrogen has a low atomic weight and when associated with a heavier atom produces both an absorption band sited in the near infra-red and a highly anharmonic vibration. Consequently, absorption overtones are found throughout the visible and near-infra-red. A similar effect is observed when a glass contains the OH radical as an impurity (see publication P3.2).

Further restrictions on the choice of a suitable liquid are set out in P2.1. Numerous liquids are available which satisfy the requirements, but all have a refractive index lower than 1.45. Guidelines for the choice of a suitable liquid are: (a) it must be fully halogen substituted to eliminate the hydrogen from the structure, (b) of the halogen substituting agents only fluorine and chlorine are suitable owing to the absorption produced by the presence of free bromine or iodine and (c) organic compounds containing oxygen or nitrogen are unsuitable owing to the proximity of their IR absorptions. One has little remaining choice but to start with the low molecular weight organic chlorine or fluorine compounds and work up in molecular weight until the refractive index becomes sufficiently large. Unfortunately, the compounds are usually found to be solids before this occurs. However, during the course of the exercise it was noticed that the addition of an ethylenic linkage imparts a higher molar refractivity to the compound, and it was by this means that hexachlorobuta-1,3-diene (HCBD) was discovered. Largely as a result of its two ethylenic linkages, HCBD has a considerably higher refractive index than the only other suitable low-loss liquids known, namely carbon tetrachloride and tetrachloroethylene. One other compound which was unearthed, but which has not yet been tried, is hexachloropropene. It is probably that this liquid will also have low loss, although it does not possess as high an index as HCBD. In addition it is highly poisonous.

A high-pressure (1400 atmospheres) filling machine was designed and built to produce long lengths of HCBD-filled, ME1-clad fibres in as short a time as possible (Fig.2.1). The machine is based upon a constant-torque motor which applies a regulated force of up to 3000kg to a piston by means of a screw. The piston moves within a cylinder containing the liquid which is forced into the fibre through a hypodermic needle fixture. A theoretical analysis of the filling process was made (publication P1.2, p306) and this enabled optimisation of both the dimensions of the fibre capillary and the filling time. It was now possible to fill a 1km length in about 30 hours. A photograph of a typical fibre having an outside diameter of 150μm and a bore of 100μm is shown in Fig.2.2.

2.2 Attenuation Results (P1.2, P2.1)

The combination of ME1 tubing filled with HCBD produced what was then the remarkably low loss of 5.8dB/km at 1.06μm. A description of the fibre and details of the attenuation may be found in publications P1.2 and P2.1. The result was all the more significant since commercially-available compound glass tubing, having an attenuation in the region of 1500-3000dB/km was used, clearly demonstrating the advantage of a large core/cladding index difference. It was estimated[3] that the high loss cladding was contributing only 1-2dB/km to the overall attenuation, although this depends on the fibre excitation conditions and length (see P5.3). The figure of 5.8dB/km remains the lowest loss ever reported in a liquid-core optical fibre.

2.3 Discussion

The achievement of low attenuation in kilometre lengths of fibre provided valuable experience in both fibre production technology and particularly in fibre propagation studies, as may be seen from Section II of this thesis. The fibre remains the closest approximation to a perfect homogeneous-core optical waveguide yet produced, and as such may be used to simulate other, less-perfect waveguides by deliberately introducing controlled defects. Expertise in the purification of liquids was acquired, since HCBD of sufficiently high quality could not be obtained commercially. Both vacuum distillation and column chromatographic techniques were used and this knowledge was later put to good use in the development of silica waveguides (Chapter 3). Furthermore, the excellent propagation properties of the waveguides verified the performance of the fibre-drawing machine and indicated a high degree of diameter stability and reproducibility. Numerous ME1/HCBD fibres were produced, both for propagation studies in our own laboratories and for supply to others at home and abroad. The ability to transmit light over kilometre lengths produced an insatiable demand for fibres, particularly since at the time the HCBD fibre claimed the lowest recorded loss. Furthermore it was the only low-loss guide of any type available in the United Kingdom.

To demonstrate the low attenuation of the fibre in more tangible terms and to provide a foretaste of optical fibre communication systems in the future,a simple transmission link was constructed. The equipment captured the imagination of the media and received wide publicity. Although signal transmission over short lengths had been demonstrated before, it was now possible to send a colour television channel over a realistic distance of more than one kilometre using only an inexpensive commercial light-emitting diode transmitter and an avalanche photodiode detector. The experimental link is shown in Fig.2.3. The equipment was used in January 1973 by the British Broadcasting Corporation to demonstrate the first live television broadcast to be transmitted through 1km of optical fibre.

References

1. Ogilvie, G.J., Esdaile, R.J. and Kidd, G.P.:'Transmission loss of tetrachloroethylene-filled liquid-core fibre light guide', Electron. Lett., 1972, 8, pp 533-534.

2. Stone, J.:'Optical transmission in liquid-core quartz fibres', Appl. Phys.Lett., 1972, 20, pp 239-240.

3. Roberts, R.:'Propagation characteristics of multimode dielectric waveguides at optical frequencies' in 'Trunk Telecommunications by Guided Waves', IEE Conf. Publ. 71, 1970, pp 39-45.

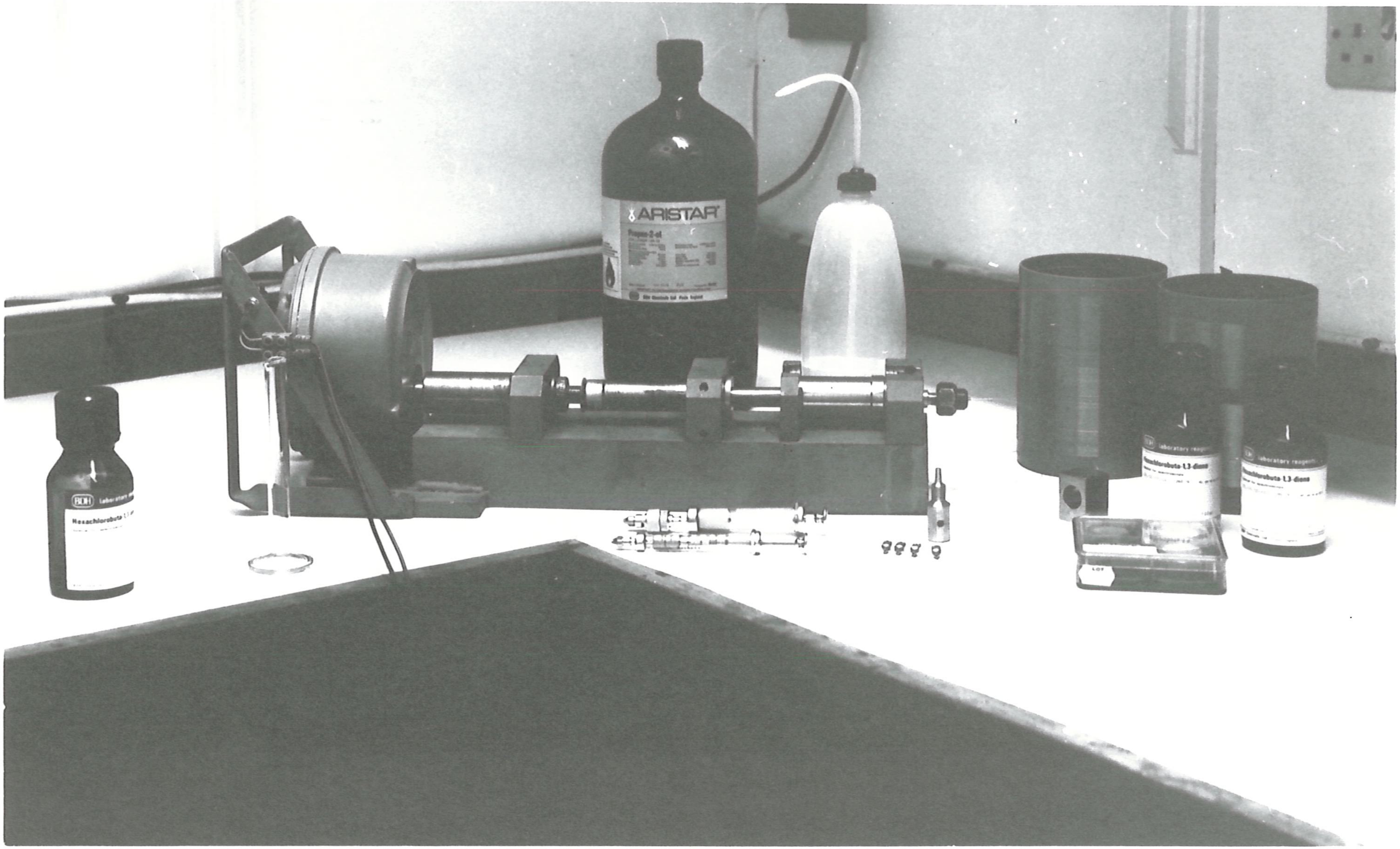


FIG.2.1 HIGH-PRESSURE FILLING MACHINE FOR LIQUID-CORE FIBRES

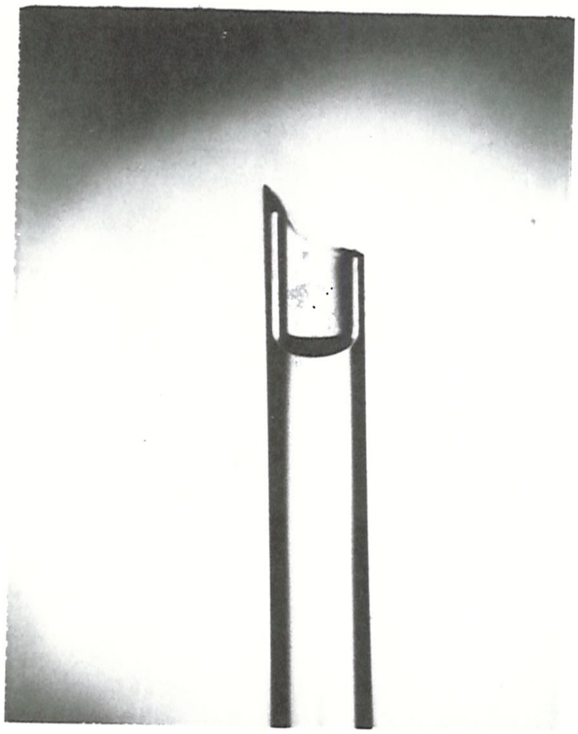
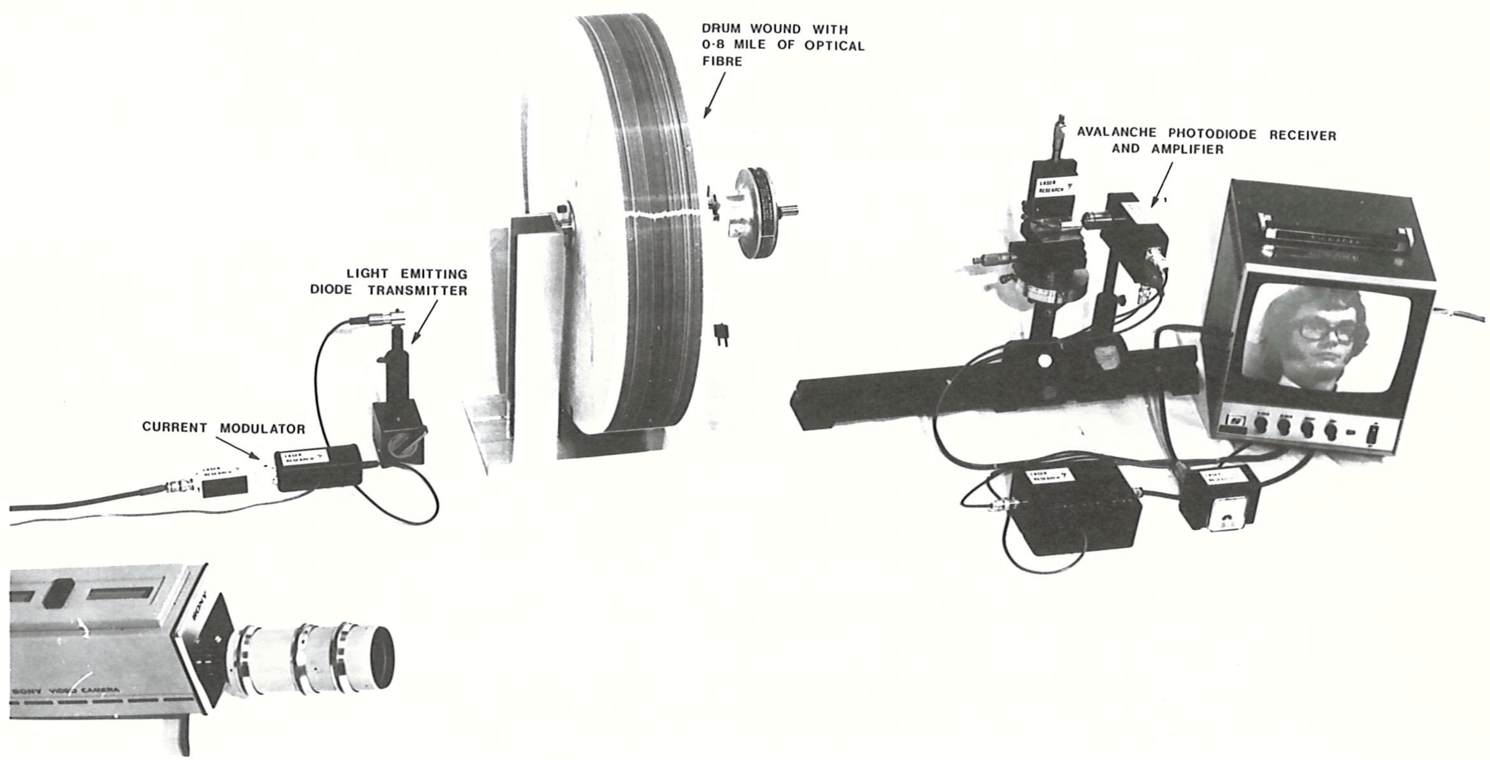


FIG.2.2 LIQUID-CORE FIBRE END
BORE 90μM, O.D. 140μM



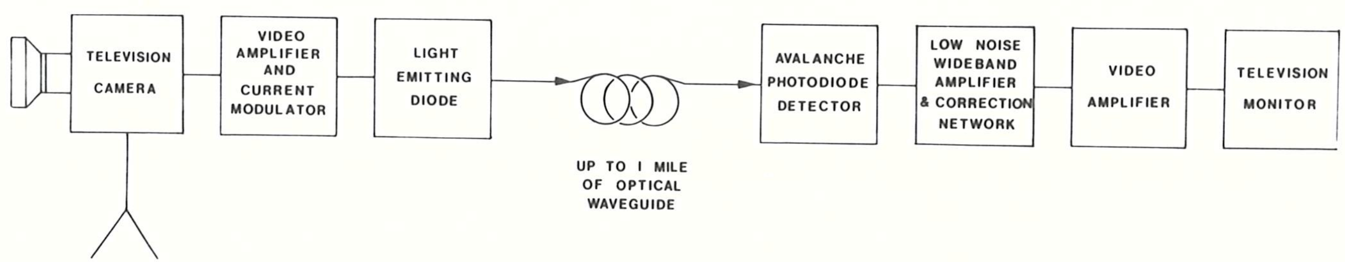


FIG. 2.3

FIBRE OPTICAL TELEVISION LINK – SCHEMATIC DIAGRAM

PUBLICATION P2.1

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

10.1049/el:19720273

CHAPTER 3

THE DEVELOPMENT OF PHOSPHOSILICATE FIBRES

3.1 Silica Fibre Drawing

Whereas liquid-core fibres provided the first demonstration of low attenuation, they suffer from several disadvantages and it was apparent that a solid-core waveguide would furnish a more attractive solution. Although the handling problems experienced with liquid cores are not intractable, they demand careful engineering. For example, it is necessary to provide liquid reservoirs and to permanently pressurise the fibre to avoid 'vapour pockets' which are formed by the action of gravity when a change in ground level is negotiated. In addition the long-term stability of a liquid core is questionable. These effects, coupled with the fact that little further improvement could be expected in the HCBD/ME1 fibre, caused us to institute research into an alternative low-loss waveguide.

Early in the development of optical fibres[1], it was apparent that certain commercially-available, synthetic grades of fused silica exhibit low attenuation. These materials are prepared by vapour deposition techniques utilising oxidation or hydrolysis of volatile silicon compounds such as silicon tetrachloride or silane. The low observed losses arise in part from the low level of contamination of the silica by the transition metals which can cause considerable absorption loss. These impurities are largely excluded from the silica because the vapour pressure of their chlorides and hydrides are very much lower than that of the corresponding silicon compounds. Therefore when the silicon compounds are vapourised, as part of the preparation process, the potential impurities are left behind and do not become incorporated within the silica. The situation is further improved by the fact that vapour deposition processes do not involve prolonged heating in furnaces - a process which can easily give rise to contamination.

It was thus decided to investigate the drawing of silica fibres from commercial silica rods or tubes. Further incentive for this was given by the earlier reports[2] from Corning Glass Works in the U.S.A. of a 20dB/km single-mode fibre made by blowing a titania-doped silica soot from an oxyhydrogen flame into a silica tube where it deposited on the inside walls. The fibre was made by collapsing the tube into a solid rod and pulling. In addition, reports[3] from Bell Telephone Labs described the production of low-loss guiding structures using only fused silica, known as 'single-material fibres. Finally it was felt that it would be instructive to provide the liquid-core fibre with a low-loss silica cladding.

3.2 The Graphite Resistance Furnace (P3.1)

A disadvantage of silica is its high working temperature; it requires a fibre-drawing temperature in excess of 2000^{o}C. In accord with the policy of precision fibre drawing outlined earlier, it was decided to develop a graphite resistance furnace rather than to rely on the poorly-controlled oxyhydrogen flame burner used by other laboratories. Fortunately this rather radical step was rewarded and it proved possible to pull very accurate silica fibres in this way. A full description of the furnace design is given in publication P3.1. Initially some difficulty was experienced in operation of the furnace due to arcing between adjacent segments of the heating element. This was overcome by increasing the clearances and the furnace has operated successfully ever since. The experience gathered in the design of the earlier low-temperature furnace (Chapter 1) permitted a design which is both novel and trouble-free. More recently a commercial design has appeared on the market, but this is believed to be rather less convenient in use as a result of its extended warm-up period. Thus it would appear that despite being the first resistance-heated graphite furnace to be used for optical fibre drawing, the design remains very competitive. It has been successfully reproduced by two industrial concerns, one British and one North American.

With the aid of the new furnace, precision silica fibre drawing proved no more difficult than for compound glass fibres. It was therefore now possible to draw lengths of several kilometres of high quality silica fibre capillary for filling with HCBD. As we had expected,the results obtained with such a fibre represented only a marginal improvement over those obtained with an ME1 glass cladding, even though the loss of the silica cladding is considerably lower. This experiment therefore confirmed that the cladding contributed little to the overall liquid-core fibre attenuation.

Further experiments in silica fibre drawing were conducted in conjunction with C.R.Hammond and S.R.Norman. For example, samples of single-material fibres were fabricated using a silica rod supported on thin glass plates within a silica tube. Losses of 36dB/km were achieved at 0.633μm, although the fibre proved difficult to handle.

3.3 The Homogeneous Chemical Vapour Deposition Process (3.5)

In January 1974 the first experiments were conducted on a new method of silica fibre production, termed, in the Southampton laboratories, the homogeneous (or modified) chemical vapour deposition technique. The earlier reports of the Corning single-mode flame process[2] and later reports from Bell Telephone Labs[4] describing the use of a dilute silane oxidation reaction to deposit a borosilicate cladding for use with a pure silica core, inspired a search for an effective means of exploiting the low-loss properties of synthetically-produced silica.

The chemical vapour deposition (CVD) process, as used by Bell Telephone Laboratories[4], is familiar in the semiconductor industry where it is used for the production of glassy passivation layers. It suffers from the disadvantage that it requires a homogeneous deposit to be produced on a surface by a heterogeneous reaction of the gas molecules at the surface. This can only occur a low temperatures and with the reactants sufficiently diluted to prevent a homogeneous gas-phase reaction taking place. Such a reaction would produce a dust of fine silica particles and a poor deposit. Because high dilution is required the deposition rate is low, typically less than 0.1μm/min. Furthermore, with hydride starting materials the hydroxyl radical is incorporated into the glass fibre and produces a high overtone absorption at 0.95μm wavelength.

In order to overcome these disadvantages we used concentrated reactants in a modified process operating at high temperatures. The principle results from the observation that a flow of concentrated silicon tetrachloride vapour reacts spontaneously with oxygen at the relatively high temperature of 1400°C to form a fog of fine glass particles. These particles would adhere to the walls of a tube containing the gas, downstream from the hot zone, where they could be subsequently fused to a clear layer.

Thus halides rather than hydrides could be used, and no hydroxyl is involved in the reaction. In addition, such a homogeneous gas-phase reaction is efficient in chemical yield and produces a high deposition rate. A uniform layer of silica can be built up on the inside of a tube by traversing the hot zone back and forth so as to fuse the glass particles as they are formed. A more detailed description of this process is given in publication P3.5, together with the equipment used.

3.4 The Phosphosilicate Glass System (P3.2, P3.3)

Having discovered an efficient and rapid means of depositing silica, it remained to find a suitable additive to increase the refractive index of the deposit so that it might form the core of an optical waveguide with silica as the cladding. Bell Telephone Laboratories had reported[5] a $3SiO_2.1B_2O_3$ glass which had a lower index than silica and might therefore be used as a cladding for a silica waveguide. By now details[6] of a new Corning process had been published whereby a hydrolysed, doped soot was deposited from a flame on the outside of a mandril. The mandril was subsequently removed and the soot fused to give a clear glass. The nature of the dopant however remained a closely-guarded secret, although it is now known to be germania.

As in the case of the choice of a liquid for liquid-core fibres, the field is considerably narrowed by several constraints. Although all oxides with the exception of boric oxide will increase the refractive index of silica, an additive which forms a volatile halide or oxy-halide is required for the homogeneous CVD process. In addition, a spontaneous oxidation temperature close to that of silicon tetrachloride is needed so that the two oxides are deposited simultaneously. The binary glass ultimately formed should be compatible with a silica cladding and be stable up to the pulling temperature of $\sim 2000^oC$. The elements of Groups III, IV and V frequently have volatile halides, examples of which are $AlCl_3$, $AsCl_3$, BCl_3, $SiCl_4$, $GeCl_4$, $SnCl_4$, $PbCl_4$, $SbCl_5$ and PCl_3 (or $POCl_3$).

Initial trials using a combination of $SiCl_4$ and $POCl_3$ vapours mixed with oxygen and passed through a heated silica tube proved instantly successful. The fibre-drawing machine and graphite furnace were used in these early experiments to provide the traversing hot zone. The silica tube was mounted in the feed mechanism and driven vertically through the furnace, set to a temperature of $\sim 1400^{o}C$. Initially twelve passes were made before radially collapsing the tube to form a rod and pulling into a fibre. Losses of less than 10dB/km in kilometre lengths of step-index fibre immediately resulted, even though poor-quality silica tubes and low-purity chemicals were used as starting materials. The homogeneous CVD technique and the phosphosilicate core material were reported[7] for the first time in March 1974.

Attention now turned towards improvements in the gas-handling equipment and to the production of graded-index fibres. Purification of the starting chemicals and the use of a high-purity synthetic cladding material (Suprasil) resulted shortly afterwards in a loss of 2.7dB/km at 0.83μm. This work was reported in July 1974 (publication P3.2),together with further improvements and a dramatic reduction in hydroxyl content in August 1974 (publication P3.3).

It appears that workers at Bell Telephone Laboratories had been pursuing a similar course for the production of optical fibres. In June 1974 they reported[8] the development of low-loss fibres based on silica doped with either GeO_2 or B_2O_3. They had discovered an identical process to that described above, but used either $GeCl_4$ or BCl_3 with $SiCl_4$ as the starting materials. The incorporation of germania into the core of a waveguide was also reported at the same time by S.T.L.[9], although it is believed that their fabrication method involved the deposition of pure germania within a silica tube and subsequent diffusion into the walls to form a binary GeO_2/SiO_2 glass.

3.5 Results (P3.4, P3.5)

A period of intense activity followed in which both the new fabrication method and the new phosphosilicate system were characterised and improved. For example it was clear that the optical quality of the silica tube affected the fibre attenuation. To combat this an optical cladding of borosilicate glass was first deposited, and a composite fibre having a borosilicate cladding and a phosphosilicate core was produced. The improved fibre was reported in publication P3.4. It has the dual advantages of (i) a higher numerical aperture and (ii) independence from the quality of the starting tube. The silica tube now acts only as a supporting structure and in fact can be replaced by virtually any tube capable of withstanding the high temperatures experienced during the deposition stage. An inexpensive 96% silica product known as Vycor has been successfully used.

Phosphosilicate glass as a core material is unique in the apparent ease with which the hydroxyl impurity which plagues other waveguides can be eliminated. It is also free from the oxygen deficiency which produces an increased absorption at shorter wavelengths in germania-doped waveguides. As a consequence of these advantages, the lowest attenuation ever recorded in an optical fibre, 0.47dB/km at 1.23μm, has been achieved in a borosilicate/phosphosilicate fibre. It is difficult to see how this result, announced recently by a Japanese laboratory[10], can be improved upon.

Publication P3.5 gives details of the properties of phosphosilicate glasses and of the production of graded-index fibres. An automatic deposition machine has been constructed by C.R.Hammond to replace the earlier method of fabrication. Experiments are continuing to attain closer control of diameter and index profile, together with an investigation of the attractive ternary glass systems based on germania/phosphosilicate and boric oxide/phosphosilicate.

3.6 Single-mode Fibres (3.5)

The homogeneous CVD technique is particularly suited to the production of single-mode fibres. By suitable choice of deposition conditions, the diameter and refractive index of the core may be varied over a wide range. A typical monomode fibre has a core of 4μm and a core/cladding index difference of about 0.3%. This may be provided by a layer of phosphosilicate glass of appropriate composition, deposited in a single pass on the inside of a silica tube. The time taken for manufacture is thus very short compared to that for the 50 or so passes required for a multimode fibre. The attenuation results so far obtained for monomode fibres have not been as low as for multimode fibres, probably because a greater proportion of the optical power propagates in the relatively lossy cladding region. However, a loss of 6.1dB/km at 0.633μm has been achieved. Work is in hand to deposit both the core and the cladding and thus ensure that propagation is confined to regions of low optical attenuation.

3.7 Discussion

It is interesting to speculate on the future of the homogeneous CVD technique. As a result of its simplicity and reproducibility it has now been adopted by all major laboratories engaged in optical communications research. So far the only additive materials extensive used with the process have been germania, boric oxide and phosphorus pentoxide, although limited reports of alumina[11] and fluorine[12] doping have been made. The mainstays of the process are the ease with which very low losses may be obtained, the ability to produce accurate refractive-index profiles, and the low capital investment involved. It has however been argued that, as a batch process, it is unsuitable for mass production, although it should be possible to extend the batch size from the current 1-2km to about 7-8km. No doubt the ultimate decision as to the most appropriate fabrication technique will rest on economic arguments and the type of fibre required. Should the telecommunications network demand very low loss (less than 2dB/km) graded-index or single-mode fibres, it is hard to see how other methods of manufacture would be competitive, particularly since they have yet to demonstrate ultra-low attenuation.

References

1. Kao, K.C. and Hockham, G.A.:'Dielectric-fibre surface waveguides for optical frequencies', Proc. IEE, 1966, 113, pp 1151-1158.

2. Kapron, F.P., Keck, D.B. and Maurer, R.D.:'Radiation losses in glass optical waveguides', Appl. Phys. Lett., 1970, 17, pp 423-425.

3. Kaiser, P., Marcatili, E.A.J. and Miller, S.E.:'A new optical fibre', Bell Syst. Tech. J., 1973, 52, pp 265-269.

4. French, W.G., Pearson, A.D., Tasker, G.W. and MacChesney, J.B.: 'Low-loss fused silica optical waveguide with borosilicate cladding', Appl. Phys. Lett., 1973, 23, pp338-9.

5. Van Uitert, L.G., Pinnow, D.A., Williams, J.C., Rich, T.C., Jaeger, R.E. and Grodkiewicz, W.H.:'Borosilicate glasses for fibre optical waveguides', Mat. Res. Bull., 1973, 8, pp 469-476.

6. Shultz, P.C.:'Preparation of very low-loss optical waveguides', 75th Annual Meeting of the American Ceramic Society, April 1973, Cincinnati, Ohio.

7. Payne, D.N.:'Comments made at Electro-Optics International, Brighton, England, March 1974.

8. French, W.G., MacChesney, J.B., O'Connor, P.B., and Tasker, G.W.:'Optical waveguides with very low losses', Bell Syst. Tech. J., 1974, 53, pp 951-954.

9. Black, P.W., Irven, J., Byron, K., Few, I.S. and Worthington, R.:'Measurements on waveguide properties of GeO_2-SiO_2-cored optical fibres', Electron. Lett., 1974, 10, pp 239-240.

10. Horiguchi, M. and Osanai, H.:'Spectral losses of low-OH-content optical fibres', Electron. Lett., 1976, 12, pp 310-312.

11. Kobayashi, S., Nakagome, H., Shimizu, N., Tsuchiya, H. and Izawa, T.:'Low-loss optical glass fibre with Al_2O_3-SiO_2 core' Electron. Lett., 1974, 10, pp 410-411.

12. Mühlich, A., Rau, K., Simmat, F. and Treker, N.:'A new doped synthetic fused silica as bulk material for low-loss optical fibres', First European Conf.on Optical Fibre Communication, London, Sept. 1975 (post-deadline paper).

PUBLICATION P3.1

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

Payne, David N. and Gambling, W.Alec (1976) A resistance-heated high temperature furnace for drawing silica-based fibres for optical communications. *American Ceramic Society Bulletin*, 55 (2), 195-197.

PUBLICATION P3.2

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/el:19740231

PUBLICATION P3.3

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/el:19740265

PUBLICATION P3.4

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: https://doi.org/10.1016/0030-4018(75)90137-6

PUBLICATION P3.5

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/piee.1976.0129

SECTION II

PROPAGATION EFFECTS IN STEP-INDEX FIBRES

CHAPTER 4

PROPAGATION IN PARTIALLY-EXCITED, STEP-INDEX, OPTICAL FIBRES

4.1 Early Experiments (P4.1, P4.2)

A programme of propagation studies was conducted concurrently with the fabrication studies described in Section I. In this way the fibres could be evaluated as they were produced and a greater insight obtained into their individual characteristics. Since the fabrication emphasis was on multimode, step-index guides, rather than on the high-capacity, single-mode fibres being investigated elsewhere, the bandwidth which could be achieved with our guides was of critical importance if they were to be competitive. Estimates[1] based on the transit time difference between rays at various angles to the axis predicted a signalling rate not much better than a few Mb/s over a kilometre, thereby limiting the prospective applications to relatively low-capacity links. With this in mind, experiments were conducted on F7/ME1 guides using a mode-locked helium/neon laser with the aim of clarifying the fibre transmission capability. The present chapter describes the initial work from the first experiments to the development of a theoretical model of fibre propagation.

The first publication (P4.1) is concerned with one of the early experimental techniques used in our propagation studies. It describes a simple index-matching mount for termination of the fibre. A procedure for obtaining a flat end in which the fibre is scored under tension is also described. The latter technique has subsequently been put on a more quantitative basis by Gloge et al[2] and is widely used today to terminate silica guides. It has proved rather easier to obtain optically flat ends in this way on silica fibres than on the earlier compound glass fibres with their thin cladding. The principle of index matching at fibre junctions or terminations set forth in P4.1 remains an important one if reflection losses are to be avoided.

The following paper P4.2, reports the first measurement made with the mode-locked laser, and represents one of the earliest attempts at interpretation of the widely varying claims for pulse dispersion in step-index guides. Fibre losses at that time were in the region of 0.3dB/m; consequently the maximum length which could be used for observation of dispersion was about 50 metres. For lengths greater than this, the pulse became buried in noise. Since the difference between input and output pulse widths was not large over this distance, the time resolution available was severely limited. Nevertheless a measure of the fibre bandwidth was obtained, indicating that, with care, the transmission capacity could be considerable - of the order of hundreds of Mb/s per kilometre.

It is interesting to trace the ideas which were emerging at the time. They may be summarised as follows.

a) The pulse broadening was found to be strongly dependent on the launching conditions in a homogeneous-core fibre. Our experiments had been performed with a well-controlled laser beam and consequently we were able to selectively launch lower order modes.
b) It was appreciated that light propagating in the cladding could affect the results. The stripping of these 'cladding modes' is now commonplace in nearly all fibre measurements.
c) The observed dispersion was to a degree dependent on the fibre under test. This problem is very much with us today; it is still difficult to use the results obtained on one fibre to describe the performance of another apparently similar guide. The reasons for this are founded in the sensitivity of the pulse dispersion to small changes in fibre parameters and in the statistical nature of the fibre deformities produced by external forces (Chapter 5).

These early experiments and the understanding which accompanied them resulted in the development of a theoretical model of fibre propagation, described in the following section.

4.2 Propagation Model for Pulse Dispersion (P4.3, P4.4)

The observation that careful control of the injected mode distribution could lead to low pulse dispersion indicated that scattering of light into higher modes was low in our fibres. This was a radical suggestion. Reports made later in the year by Bell Telephone Laboratories[3] claimed that total mode mixing occurred within one metre, whereas we were observing little conversion in 50m. However, recalling Section I, the achievement of lower loss in F7 core fibres had been accomplished by improvements in the quality of the core/cladding interface and this, together with the close diameter control, naturally led to lower mode conversion. It is intriguing to observe that the progress started in these early experiments is still going on. The achievement of lower and lower attenuation is invariably accompanied by a reduction in mode scattering. For example, kilometre lengths of phosphosilicate fibre exhibit very little mode conversion and other reports[4] suggest that waveguides can be made with such perfection that propagation over 10km fails to produce full mode mixing. However, as will be detailed in Chapters 5 and 6, it is not only manufacturing defects which cause mode coupling. Externally applied pressure has a similar effect to that produced by interfacial imperfections and this must ultimately also be taken into account.

The availability of high-quality fibres and the observation of a low degree of mode mixing prompted a theoretical analysis of pulse propagation and the effect of launching conditions on pulse dispersion. Details of the analysis are recounted in publication P4.4. The paper should be read in conjunction with P4.3 which describes transmission experiments aimed at verifying the results of the analysis. The level of agreement between theory and experiment shown in the two publications is good. Thus for the first time it was possible to predict theoretically the pulse performance of a fibre from a knowledge of the launching conditions.

The analysis is based on several simplifying assumptions. These are (i) that the normalised frequency V of the waveguide is sufficiently large that there is effectively a continuous mode spectrum, enabling a ray-optical model to be used; (ii) that the phase velocity in the guide is very nearly equal to the group velocity so that the ray path length may be used to determine the transit time; (iii) that both mode scattering and differential modal attenuation are absent so that the modal power distribution within the guide is entirely dictated by the launching conditions and the output mode spectrum is identical to that at the input; (iv) that the waveguide materials are non-dispersive. In other words the analysis is restricted to a perfect, lossless, highly-overmoded guide. The validity of these simplifications may be judged by the high level of agreement obtained with the experimental results. Conversely, and of equal importance, the agreement may be used as an indication of the degree of perfection achieved in the guide.

An example of the latter is given by Fig.3 of P4.3, depicting the pulse dispersion after 43 metres of F7/ME1 fibre, measured as a function of the launched beam half-angle. Our theory predicts a pulse dispersion which dramatically reduces as the beam half-angle becomes smaller, when only very low-order modes should be excited. However an increasing discrepancy between theory and experiment is seen once the excitation conditions favour lower-order modes. Apparently the output modal distribution remains substantially unchanged for small angle excitation. This is a clear indication that some small degree of mode scattering exists in the waveguide. Thus assumption (iii) above is not strictly accurate for this fibre, at least under low-order mode excitation conditions.

It is now known that the lowest-order modes of a step-index guide are particularly sensitive to mixing, this being induced by bends and kinks in the fibre. The difference in propagation constants between adjacent modes determines which modes will be coupled by a given fibre axis deformation. The difference becomes less as the mode order reduces ; consequently coupling can be caused by relatively low-frequency spatial modulation of the waveguide axis, such as gentle bends. Further discussion of this effect may be found in Chapters 5 and 6.

A more recent result testifying to the accuracy of the theory when little or no mode conversion is exhibited is presented in Fig.4.1. The trace displays the output pulse from 600m of liquid-core fibre at a sweep speed of 5ns/div. The exciting beam half-angle was 8^{o} and the input pulse had an approximately Gaussian form of 200ps full-width at half-maximum. Reference to Figure 2(a) of P4.4 indicates a remarkable similarity between the predicted and observed pulse shapes. The measured pulse width of 10.5ns agrees closely with the theoretical prediction of 10.2ns, thereby indicating that no significant mode conversion had occurred in this fibre. It should be noted however that the susceptibility of the lowest-order modes to mode mixing may nevertheless be seen in the distortion of the leading edge of the pulse. The low-order modes have the highest group velocity, and therefore constitute the start of the pulse. The relatively slow rate of rise of the leading edge is an indication that some mode mixing has occurred.

The conclusions reached through the analysis are that the pulse dispersion in a step-index multimode guide is strongly dependent on the launching conditions, and therefore the broadening reported in P4.2 is not at all inconsistent with the experimental conditions. Thus previous predictions for the bandwidth of the guides were excessively pessimistic, and acceptable performance can be obtained by ensuring that only low-order modes propagate, either by careful launching, or by the use of a fibre having a low numerical aperture. The theoretical model now enabled interpretation of both the observed pulse shapes and the pulse dispersion, and could be used as an indication of the degree of mode mixing occuring in the guide.

The results for the impulse response of a step-index fibre presented in P4.4 have since been rederived by other workers using different means[5,6]. The conclusions reached are identical to those presented here for Lambertian excitation, since the later work assumes the simpler case of full mode excitation.

<u>4.3 Mode Filtering</u> (P4.5)

Following the realisation that mode conversion could be remarkably low in well-made fibres, a method of eliminating the small proportion of power diffusing to higher-order modes was proposed in publication P4.5. The idea was that restrictions in the form of tapers should be used at intervals along the fibre to strip higher modes from the waveguide as they become excited. In retrospect, this suggestion is not really a practical proposition as it would effectively trade loss for bandwidth - normally an unacceptable exchange. However, the idea of using tapers to strip higher-order modes has since been extensively used, both for diagnostic purposes[7] and to couple between two parallel fibres[8].

In a multi-access communications system, where power must necessarily be tapped from the waveguide periodically, it would be advantageous to remove the higher order modes in the way suggested and thereby improve the system bandwidth. For example, a taper formed in situ at a desired tapping point has the dual function of extracting power from the waveguide and of improving the overall system bandwidth. Since the proportion of power radiated from the taper depends on the degree of excitation of the higher modes in the waveguide, it is possible to produce a variable tapping ratio by introducing controlled mode mixing immediately upstream of the taper. This can be achieved by the application of applied pressure or kinking to scatter light into higher modes.

References

1. Williams, D. and Kao, K.C.:'Pulse propagation along glass fibres', Proc. IEEE, 1968, pp 197-198.

2. Gloge, D., Smith, P.W., Bisbee, D.L. and Chinnock, E.L.: 'Optical fibre end preparation for low-loss splices', Bell Syst. Tech. J., 1973, 52, pp 1579-1588.

3. Gloge, D.:'Optical power flow in multimode fibers', Bell Syst. Tech. J., 1972, 51, pp 1767-1783.

4. Cohen, L.G.:'Pulse transmission measurements for determining near-optimal profile gradings in multimode borosilicate optical fibers', Appl. Optics, 1976, 15, pp 1808-1814.

5. Cozannet, A. and Treheux, M.:'Skew rays in optical fibers', Appl. Optics, 1975, 14, pp 1345-1350.

6. Arnaud, J.A.:'Beam and Fiber Optics', Chapter 4, Academic Press, New York, 1976.

7. Midwinter, J.E.:'The prism-taper coupler for the excitation of single modes in optical transmission fibres', Optical and Quantum Electron., 1975, 7, 297-303.

8. Ozeki, T. and Kawasaki, B.S.:'Optical directional coupler using tapered sections in multimode fibers', Appl. Phys. Lett., 1976, 28, pp 528-529.

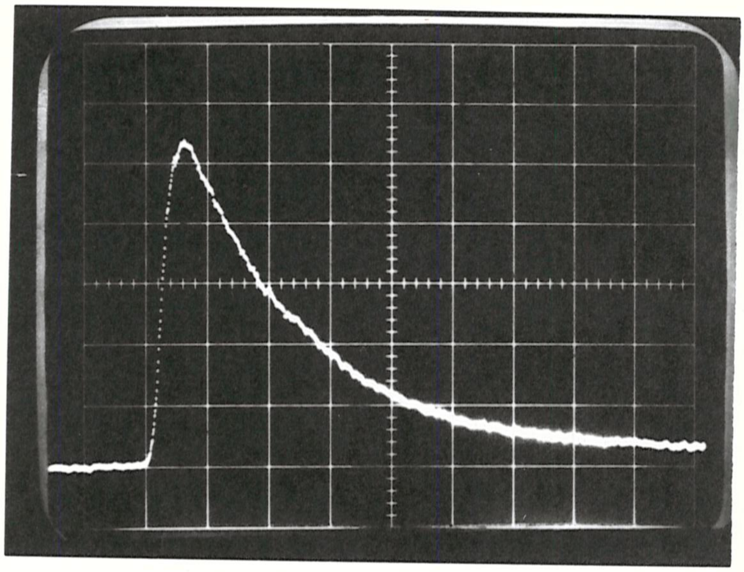


FIG.4.1 OUTPUT PULSE FROM 600 METRES OF HCBD/ME1 FIBRE
5NS/DIV

PUBLICATION P4.1

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: https://doi.org/10.1016/0030-4018(72)90076-4

PUBLICATION P4.2

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/el:19710371

PUBLICATION P4.3

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/el:19720192

PUBLICATION P4.4

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: https://doi.org/10.1016/0030-4018(73)90096-5

PUBLICATION P4.5

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/el:19720193

CHAPTER 5

PULSE DISPERSION IN LIQUID-CORE FIBRES

5.1 Initial Measurements (P5.1)

The attainment of low loss in the HCBD/ME1 liquid-core waveguide (Chapter 2) permitted pulse propagation studies on long lengths of fibre to be made for the first time. Although the loss at 0.633µm was usually in the region of 50dB/km, the mode-locked helium-neon laser with its well-controlled beam could now be transmitted through several hundred metres. In addition, a pulsed GaAs laser operating at 0.9µm was available and permitted measurements over a kilometre length.

The earlier work on partial excitation of solid-cored fibres had raised the question of whether the power could be maintained in low-order modes over substantial distances, or whether uncontrolled mode mixing would yield increased dispersion due to eventual excitation of the higher-order modes. In addition, it was appreciated that a degree of preferential attenuation of the higher-order modes existed as a result of the large absorptive loss of the ME1 cladding material, although this did not appear to contribute significantly to the overall attenuation. A second question was therefore raised as to what effect this differential attenuation would have upon the pulse dispersion. A programme of measurements on the new fibre was initiated in conjunction with H. Matsumura to investigate the above effects.

Basically two observations can be made to assess the degree of mode conversion and preferential attenuation in a step-index fibre. They are (i) determination of the output far-field distribution and comparison with the input field and (ii) measurements of the relationship between the time-dependent pulse transmission characteristics and the theoretical predictions of Chapter 4.

Initial experiments were made on up to 310m lengths of fibre with the helium-neon laser. The results are reported in publication P5.1. Referring to the paper, it is immediately apparent that a similar effect to that reported earlier (Chapter 4 and P4.3) for solid-core fibres is also present in liquid-core guides; namely that a continued reduction of the angular spread of the input beam does not ultimately cause transmission of only the lowest-order modes. Thus a degree of mode-mixing exists in the guide and this prevents the output mode spectrum reflecting that at the input when only the lowest modes are launched. As a consequence, the pulse dispersion cannot be arbitrarily decreased to some very low value by appropriate choice of excitation conditions. Furthermore, two other effects were noticed; namely that the degree of mode mixing appeared to depend on both the core diameter and the radius of the drum on which the experimental fibres were wound. In an effort to explain the former, the fibre loss was measured as a function of the angle a ray made to the axis. It was reasoned that, due to the larger number of reflections of a 'ray' at the core/cladding interface, a small core fibre would experience higher differential attenuation and therefore transmit fewer slow modes. Although this effect may in part account for the lower observed pulse dispersion, it is now appreciated that a smaller core fibre can be expected to have lower mode-coupling on two counts. Firstly, the cladding thickness of the small-core fibre is larger than that of the 87μm core fibre, resulting in greater fibre stiffness. It will be shown in a later section that strong mode coupling is caused by small but sharp deformations of the fibre axis. The higher resistance to deformation by external forces exhibited by the small-core fibre may consequently be expected to result in lower mode mixing. Secondly, the smaller core fibre has a lower normalised frequency V and it follows that the modes are spaced more widely in propagation constant β . Now when the frequency of a spatial deformation matches the β difference between modes, coupling will occur[1]. Therefore, in general, a smaller core fibre requires a higher frequency deformation to induce mode mixing than a larger fibre. Together with the increased stiffness of the former, which imparts a greater resistance to short wavelength deformation, this will reduce the susceptibility to mode conversion.

The curves for attenuation of a 'ray' as a function of angle of propagation are instructive in understanding how a waveguide with a cladding loss of several thousand dB/km can achieve an overall attenuation of less than 10dB/km. It may be seen that, provided the optical power is contained within a cone having a half-angle of less than 10° to the axis, negligible additional loss will be incurred.

5.2 Mode Conversion Induced by Microbending (P5.2)

The increased mode mixing observed when the fibre was wound on drums of smaller diameter is pursued in more detail in publication P5.2. Measurements were made of (i) the output far-field distribution and a comparison made with that at the input; (ii) the group delay as a function of the angle at which a plane wave is launched to the axis; (iii) the pulse dispersion for various excitation conditions. The experiments were conducted with the fibres wound on a series of expanded polystyrene drums having different diameters. A clear dependence of the degree of mode mixing on the bend radius was observed, suggesting that if power was to be confined to the low-order modes and a low dispersion maintained, care would have to be exercised in negotiating bends. A bend radius of 55mm was found to degrade the bandwidth by almost an order of magnitude compared to one of 970mm. This dependence of mode scattering on the rate of change of direction is well known in overmoded waveguides at microwave frequencies; however it was surprising it occurred at a bend radius of greater than 10^6 times the operating wavelength!

It is now recognised that the effect we had observed was the first characterisation of an important phenomenon, latterly named 'microbending'[2,3]. As the name suggests, it refers to the mode conversion induced in a fibre by small kinks or bends in the axis, produced for example by passage over a rough surface. It has been shown[1] that perturbations of the fibre axis which have a periodicity in the propagation direction equal to the beat wavelength between two modes results in strong coupling of the modes. The beat wavelength is the distance within which the phase of one of the modes lags a total of 2π behind the other. The concept may also be applied to non-periodic perturbations, such as random bends, if the Fourier 'power' spectrum of the axis deformation is known.

The fibres in our experiments were wound at constant tension onto expanded polystyrene drums having a degree of surface roughness. Thus, if the random surface roughness contained frequency components corresponding to the beat wavelength between modes, coupling would result. The fibres of P5.2 have a characteristic beat wavelength ranging from 600μm for coupling between adjacent highest modes, to a few centimetres for mixing to occur between the lower pairs. The drums were certainly not smooth on a millimetre scale, so preferential coupling of the lower modes could be expected, and indeed occurred. The apparent dependence on bend radius is explained by the use of a constant tension rewinding machine. It can readily be appreciated that the radial pressure exerted by the fibre on the drum (and vice versa) is inversely dependent on the bend radius if the tension is kept constant. Thus the degree of perturbation of the axis depends on the drum radius, since the increased radial pressure on the smaller drums causes greater conformity of the fibre to the rough surface. Once this fact was appreciated, the experiments were repeated with the fibre taken off the drum, when considerably less mode conversion was found. The results of this experiment are reported in the next chapter.

Following this first experiment, microbending has been recognised as a major problem in the cabling of fibres, where its presence may cause large additional fibre losses. Although the mode conversion observed in our experiments only resulted in a greater proportion of modes becoming excited (since the fibres were not fully excited), conditions of excessive axis perturbation, such as might be experienced with a poorly-constructed plastic protective layer, could result eventually in full fibre excitation. Once this is achieved further mode conversion couples light from the guide as a radiation loss. The effect is commonly observed in cabled fibres. It is accentuated in more recent fibres produced by CVD by their low numerical aperture (0.18). This compares with a figure of 0.47 for the HCBD fibre.

5.3 Effect of Loss on Propagation (P5.3)

In addition to the absence of mode coupling, the theory of pulse dispersion developed in P4.4 assumes a lossless guide. Since this was demonstrably untrue in the liquid-core fibre (see P5.1), it was clear that an investigation of the effect of preferential attenuation of the higher modes was desirable. To this end the theory was modified to include the cladding loss and the accompanying mode filtering action. The calculations are given in some detail in publication P5.3, and it therefore suffices to summarise the results here.

The presence of mode filtering and the preferential attenuation of higher modes produces a spatial transient within the guide. The degree of excitation will, in general and in the absence of mode conversion, become less as we progress down the fibre. Since the pulse dispersion and the measured attenuation are dependent on the modal power spectrum, both measurements become length dependent. Thus an attenuation measurement made with full excitation at the input will depend on the length of fibre used in the determination; a low figure will only be obtained after a sufficient length for all lossy higher modes to have been removed. Similarly the pulse dispersion no longer increases linearly with length, but becomes sub-linear as the higher modes found in the latter half of the output pulse are stripped.

It would therefore appear advantageous to deliberately employ a lossy cladding to improve the bandwidth of the guide. However, again we are faced with a higher bandwidth at the expense of increased transmission loss and, as outlined earlier, this is normally unacceptable. Furthermore,a similar trade could be made by utilising apertures at the output or, better still, by using a fibre of lower numerical aperture. In the latter case the trade is seen as a reduced launching efficiency from an incoherent (LED) source. If a laser source is employed however, injection efficiency need not be compromised.

5.4 Discussion

We have seen that in order to provide a full description of transmission in step-index fibres, mode conversion as well as mode filtering must be taken into account. The comparison made in P5.3 between theory and experiment suggests that, although exceptionally low in our fibres, mode mixing introduces significant errors, particularly under excitation conditions favouring low-order mode propagation. This is because the natural stiffness of the fibre imparts a predominantly low-frequency spectrum to the inevitable fibre axis deformation, and therefore a preferential coupling of low-order modes is favoured.

A further consequence of mode scattering which must be taken into account is that an equilibrium will eventually occur between the combined effects of mode filtering and mixing[4]. Thus a continued reduction in the degree of excitation does not take place, as predicted in P5.3 for the case of mode filtering alone. Instead, an equilibrium modal power distribution will be achieved after a certain length, and this will propagate substantially unchanged provided the spatial spectrum which causes the mixing remains statistically invariant. In our liquid-core fibres this 'equilibrium' length was considerably longer than the one kilometre fibres available.

The mode filtering effect produced by a lossy cladding, first described in publication P5.3, has become increasingly important with the recent introduction of plastic-clad silica fibres[5]. It was convincingly demonstrated by the HCBD/ME1 fibre that a high cladding loss can be tolerated provided the index difference is large. Since most plastics have a large scatter loss as a result of their long chain polymer structure, it is similarly necessary to choose a plastic cladding having as low an index as possible. Following the example of our liquid-core fibre, successful FEP-clad silica guides have been made and they exhibit remarkably similar propagation characteristics to those described in P5.3. For example it is observed that the output numerical aperture from a long length of fibre is considerably less than that measured at the input, and that the pulse dispersion is a function of length[5].

5.5 Determination of the Mode-conversion Coefficient (P5.4)

By now it was appreciated that mode coupling is rarely intrinsic in a well-made liquid-core fibre. The mode scattering that is experimentally observed is almost invariably caused by externally-applied pressure. It is therefore useful to have a means of measuring the degree of mode conversion which exists when the fibre lies in a given configuration. The method we have developed is described in detail in publication P5.4. The technique is based on an equation derived by Gloge[4] for the diffusion of power to higher modes.

Basically Gloge's mode conversion coefficient D can be found by injecting a parallel beam into a fibre at an angle to the axis and observing the output far-field pattern. The point at which the latter transforms from a uniform disk to a ring enables D to be found. The major advantage of the method lies in the fact that it is not necessary to know the other parameter which can influence propagation, namely the mode filtering effect. Thus it proved possible for the first time to put mode conversion on a quantitative basis and to compare its value in various fibres, both stressed and unstressed.

The measurement of D confirmed several previously held views:

i) The mode scrambling in a liquid-core fibre is very low indeed, an order of magnitude or so less than that in the best glass fibres.

ii) The extrinsic mode conversion is considerably larger than the intrinsic under normal experimental conditions where the fibres are wound on drums. To completely remove all extrinsic effects it was necessary to lay the fibres in large unsupported coils on a flat surface. Even so, the crossing of one coil over another could produce a significant increase in D.

iii) The assumption made by Gloge of coupling only between nearest neighbours appears to be valid. This is somewhat surprising in view of later work by Olshanski[3] in which it it shown that the stiffness of the waveguide causes a perturbation power spectrum containing predominantly low-frequency components. Thus the coupling coefficient between lower-order modes is greater than that between higher modes, and is not equal as assumed in Gloge's theory. On the other hand it is probable that inclusion of the angular dependence of the coupling coefficient does not significantly change the length-dependent effects provided observations are made over a limited angular range.

5.6 <u>The Goos-Hänchen Shift</u> (P5.5)

The propagation model developed in Chapter 4 and extended in this chapter to include the effect of an angular dependence of attenuation, is based on a ray analysis. As outlined earlier, this fact places constraints on the validity of the theory, the major one being that it can only be applied to waveguides which support a very large number of modes. Even in the latter case a ray analysis is an approximation, and a modal analysis must be used if exact solutions are required. The results yielded by the ray technique are sufficiently accurate for most purposes; however if closer agreement between a ray and mode analysis is required, it is necessary to include the effect of the Goos-Hänchen shift. Details of the procedure are given in publication P5.5. The effect may be regarded as a small correction to the ray theory. The error becomes increasingly significant for rays close to the critical angle (i.e. modes near cut-off) when the zig-zag ray picture of propagation used in P4.4 provides a poor representation of light transmission. Fortunately, in a normal multimode fibre only a very few modes are close to cut-off, so the omission of the shift has negligible overall effect. This would not be the case for example in a fibre which supports only a few modes.

The validity of the ray model for a HCBD/ME1 fibre is clearly shown by Fig.2 of publication P5.5. The fibre is capable of supporting some 5000 modes and should therefore be accurately described by a ray picture. It may be seen from the figure that the well-known sec-law describing the relationship between the propagation delay and the angle to the axis is remarkably accurate. Thus it may be concluded that the Goos-Hänchen shift can safely be disregarded provided the waveguide supports sufficient modes. If this condition is met the simple ray theory developed in P4.4 may be employed for all but the most critical calculations.

A more recent detailed analysis[6] of the Goos-Hänchen shift applied to optical fibres confirms the above conclusions, and similarly deduces that the added complexity of the Goos-Hänchen shift is rarely needed.

5.7 Conclusions

In summary, the work described in this chapter represents probably the most comprehensive experimental study of mode filtering and scattering performed to date. Owing to the statistical nature of externally-induced mode mixing, the effect is notoriously difficult to characterise and therefore for definitive conclusions to be drawn. The question posed at the beginning of the chapter was whether it would be possible to maintain low-order mode excitation over long distances and thereby obtain high bandwidth. It is now clear from both the work reported here and from many, more recent, measurements that, in practice, fibres are invariably partially excited. Full mode excitation is precluded even after long lengths by a combination of mode filtering and by the very low mode conversion which is inherent in a low-loss guide. Thus a theory of pulse dispersion based on the assumption of full excitation will yield pessimistic results. On the other hand the theory of partial excitation developed in Chapter 4 ignores mode mixing altogether and therefore will be optimistic in cases of low partial excitation.

Finally we note that the experiments described here were all conducted within the spatial transient region; that is, before complete mode mixing had been achieved and an equilibrium modal distribution reached. In this case the launching conditions can influence the output distribution and the degree of partial excitation will have a strong effect on the pulse dispersion. We were not able to perform experiments on fully-mixed fibres, as the fibre length required would have been excessive. However, practical fibre cables may well be operating in a similar regime to that used here and not in the fully mode-mixed region. This is seen from recent reports[7] which suggest that full mode mixing in a low-loss fibre need not be achieved within a length of 10km. Since the repeater spacing is of this order, the equilibrium modal power distribution will never be attained.

References

1. Miller, S.E.:'Some theory and applications of periodically coupled waves', Bell Syst. Tech. J., 1969, 48, pp 2189-2219.

2. Gloge, D.:'Optical fibre packaging and its influence on fiber straightness and loss', Bell Syst. Tech. J., 1975, 54, pp 243-260.

3. Olshansky, R.:'Distortion losses in cabled optical fibers', Appl. Optics, 1975, 14, pp 20-21.

4. Gloge, D.:'Optical power flow in multimode fibers', Bell Syst. Tech. J., 1972, 51, pp 1767-1783.

5. Kaiser, P., Hart,Jr., A.C. and Blyler, L.L.:'Low-loss FEP-clad silica fibers', Appl. Optics, 1975, 14, pp 156-162.

6. Snyder, A.W. and Love, J.D.:'Goos-Hänchen shift', Appl. Optics, 1976, 15, pp 236-238.

7. Cohen, L.G.:'Pulse transmission measurements for determining near-optimal profile gradings in multimode borosilicate optical fibers', Appl. Optics, 1776, 15,pp 1808-1814.

PUBLICATION P5.1

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/el:19720413

PUBLICATION P5.2

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: https://doi.org/10.1016/0030-4018(72)90145-9

PUBLICATION P5.3

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/ree.1973.0100

PUBLICATION P5.4

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: https://doi.org/10.1364/AO.14.001538

PUBLICATION P5.5

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/el:19740077

CHAPTER 6

SINGLE-MODE PROPAGATION IN HIGHLY-OVERMODED FIBRES

6.1 Mode Selection (P6.1)

Following the realisation that mode mixing in the HCBD/ME1 liquid-core fibre was largely caused by external pressure, an attempt was made to eliminate all possible sources of distortion, and to test the fibre in its natural, unstressed state. As a first step, the fibres were removed from their supporting drums and laid in large coils on a flat surface. It was immediately found that the degree of mode mixing reduced to almost undetectable levels. Consequently the guide excitation could easily be reduced to a few modes only; ultimately it was even possible to restrict excitation to the lowest order (HE_{11}) mode. The earlier experiments which had been limited by stress-induced mode mixing could now be repeated under more favourable conditions. Furthermore, and more importantly, the capability of the fibre to transmit only a few modes suggested its use as a diagnostic tool for an investigation of mode coupling. The advantages of testing the fibre in this way are (i) the excitation of only a very few low-order modes reduces the modal analysis to reasonable dimensions; (ii) minute degrees of mode mixing can easily be detected experimentally by the break-up of the single-mode Gaussian far-field pattern. Thus the effects of pressure and bends are clearly visible, and may be isolated from any mode mixing which may be caused by intrinsic imperfections.

Initially an experiment was performed (described in P6.1) in which it was shown that the HE_{11} mode could be selectively launched and transmitted over lengths of a few metres. Previous mode selection attempts[1] had been confined to a few centimetres of fibre before waveguide scattering excited additional modes. We were now able to show that in an undistorted high-quality fibre, the levels of mode mixing could be so low as to be negligible and that the fibre behaved exactly as a highly-overmoded, perfect waveguide. The fibre could be similarly described when the experiment was later extended to lengths of 400 metres or more. Even after such a length the power could be confined very largely to the HE_{11} mode.

6.2 Mode Coupling Caused by Curvature (P6.2)

In the course of the experiments described above, it was noticed that very slight repositioning of the fibre caused the modal distribution to change. This could be seen as a break up of the single-mode, far-field output distribution into two or more patterns. Although monomode propagation could often be regained by small adjustments to the launching micromanipulator, clearly the fibre curvature had some effect on the mode spectrum. It had previously been thought[2] that constant curvature itself did not cause mode conversion and that mode scattering could only result from a change of curvature.

The high degree of perfection attained in our fibres permitted experiments to be conducted which were not previously possible, so an attempt was made to determine the effect of a simple bend on light transmission. The mode excitation spectrum was restricted to only the lowest mode so that any mode mixing could easily be seen. The conclusion of this work is reported in publication P6.2, and may be summarised as follows.

1) On entering a bend, the lowest-order HE_{11} mode is coupled to its nearest neighbours, the HE_{21} and TE_{01} modes. The coupling is a direct result of the departure of the axis from perfect straightness.
2) As is usual when two modes are coupled, the optical power will beat between the modes. That is, power interchange occurs as we progress down the waveguide, and will periodically be found either in the original HE_{11} mode or, at some other position in the waveguide, in a combination of HE_{11} and HE_{21} plus TE_{01} modes.
3) The periodicity of the beat phenomenon will be dependent on the bend radius, as will the strength of coupling and the proportion of the total power being interchanged.
4) The mode spectrum found after traversing a bend and in a region where the fibre has become straight again will depend on the length of the bend. By appropriate choice of curvature and length, it is possible to ensure that all power has been restored to the HE_{11} mode. The output from the bend will then be a single mode, as at the entry to the bend.
5) No significant diffusion of power occurs to higher modes other than those previously mentioned.

The process may be readily understood from a ray optical picture. Consider a ray representing the HE_{11} mode propagating on-axis as it enters the bend. Within the bend, the angle made by the ray to the axis oscillates about its original position, corresponding to periodic excitation of the two higher modes. The ray cyclically passes through its original position, which represents the point at which power is returned to the HE_{11} mode. The angle with which the ray re-emerges from the fibre will depend on the length of the bend, but if this is carefully chosen the ray will be found on axis again and no permanent mode conversion will have resulted.

6.3 Discussion

We see that a bend does not cause mode conversion in the sense that the longer the bend the greater will be the mode scattering. Effectively it is the change of curvature, the point at which the bend ceases, which determines the output mode spectrum. On the other hand the statement that only change of curvature causes mode coupling is equally misleading since periodic coupling occurs throughout the bend, although this is not of a diffusive nature. In order to obtain a diffusion of power from the HE_{11} mode to progressively higher modes we need a succession of curves of random lengths. In this case, the output mode spectrum from the first will in general consist of the three lowest modes, and these will form the input conditions for the second bend. In turn, these three modes will be periodically coupled to other still higher modes within the second bend, and the emergent mode spectrum will be further increased. Note, however, that if the curvature is kept very gradual, of the order of metres, it is possible to ensure that the emergent power is always maintained in the lowest order mode, and no diffusive mode coupling can occur even after a succession of bends. This is shown by Fig.5a of P6.2 where we see that negligible power transfer to higher modes occurs for a bend of 10^5 times the core radius, i.e. a bend radius of about 5 metres. The effect may be appreciated by noting that very low frequency spatial components predominate in the 'power spectrum' describing so large a curvature. As we have seen previously, a perturbation wavelength of a few centimetres is required to couple the lowest modes to one another. It is clear therefore that a large curvature will cause minimal mode coupling since the amplitude of these frequencies in the perturbation spectrum is low.

In summary, a form of quasi-single-mode propagation can be expected in a fibre carefully laid out with gradual and approximately constant curvature. The power will be constrained to propagate within the lowest 3 modes, and by careful choice of the bend length can be persuaded to emerge in only the HE_{11} mode. Under these conditions the pulse dispersion will naturally approach that of a single-mode fibre.

6.4 Pulse Dispersion for Quasi-single-mode Operation (P6.3)

The final publication in this series (P6.3) serves to make the point that all propagation measurements previously reported had been dominated by externally-induced fibre distortion. If the distorting influence is removed, then very close agreement may be obtained with simple theoretical predictions. A clear correlation between tension on the drum and both pulse dispersion and output angular distribution is shown in publication P6.3. Thus the discrepancy between the ray theory developed in P4.4 and the experiments reported in P4.3 is now resolved, and excellent agreement can be obtained by the use of unstressed fibres. The publication also underlines the importance of stress-induced microbending, and this proved invaluable in the early stages of development of the phosphosilicate fibre. Since our first examples of the fibre possessed a rather low numerical aperture (0.1), it was found that the winding tension on the drum considerably influenced the attenuation measurement. In common with numerous observations later made in other laboratories, a lower loss was measured when the fibres were slackened on the drum. The reason for this is that mode conversion caused by microbending can eventually cause excitation of all modes, particularly in low-aperture fibres. Further mode mixing then couples power to radiation modes and produces a loss.

6.5 Conclusions

From a practical viewpoint is seems unlikely that a multimode, step-index fibre will be used in a communications system under conditions of single-mode excitation, owing to both the difficulty of launching the mode and also of maintaining the fibre in a stress-free condition. Furthermore, it has already been pointed out (section 5.2) that the beat wavelength between the lowest modes is very long. Consequently we cannot rely on the natural stiffness of the fibre to 'filter out' the axis modulations which correspond to the beat wavelength, as for the higher modes. Thus even small direction changes or mild undulations of the guide on a centimetre scale will produce coupling between low-order modes and power diffusion.

On the other hand, it is possible to restrict excitation to only a few of the low order modes, as follows. Power diffusion will occur as described above, but the excitation will be limited to modes whose beat wavelength is present in the perturbation spectrum. If we ensure that the guide axis modulations are gentle, the perturbation spectrum will be lacking in high-frequency components. The natural stiffness of the fibre helps in this respect, particularly in resisting stresses which occur on a millimetre scale. Power diffusion in the guide will then take place amongst low-order modes, but will become progressively less for the higher modes with their short beat wavelength. At some level of excitation, further diffusion of power to higher modes becomes negligible and a stable mode spectrum results. Clearly, the roughness of the drums in the experiments of Chapter 5 produced only low-frequency perturbations; consequently it was possible to maintain the power in the lower-order modes. With careful cabling this should also be attainable in practice, making the use of partially-excited fibres an attractive possibility.

It is worth noting that the situation is rather different for a fibre having a parabolic index profile. Here there is only one characteristic spatial frequency which will couple modes, since the beat wavelength of all pairs of adjacent modes is very nearly equal. This wavelength is typically a millimetre or two and therefore it is more difficult to couple even the lowest-order modes together. Reports of substantially single-mode propagation in long lengths of graded-index fibre have been made[3], even though the fibre was wound on a drum.

References

1. Kapany, N.S.:'Fiber Optics', Chapter 3, Academic Press, New York, 1967.

2. Gloge, D.:'Bending loss in multimode fibers with graded and ungraded core index', Appl. Opt., 1972, 11, pp 2506-2513.

3. Koizumi, K., Ikeda, Y., Kitano, I., Furukawa, M. and Sumimoto, T.:'New light-focussing fibers made by a continuous process', Appl. Opt., 1974, 13, pp 255-260.

PUBLICATION P6.1

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/el:19730303

PUBLICATION P6.2

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

Gambling, W.A., Payne, D.N. and Matsumura, H. (1974) Propagation in curved multimode cladded fibres. *AGARD Conference on Electromagnetic Wave Propagation Involving Irregular Surfaces and Inhomogeneous Media, Netherlands.*

PUBLICATION P6.3

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/el:19740113

CHAPTER 7

MATERIAL DISPERSION IN PHOSPHOSILICATE FIBRES

7.1 Measurement of Material Dispersion (P7.1)

The development of low-loss phosphosilicate fibres (Chapter 3) naturally raised several questions about the properties of the new material. Phosphosilicate glasses had only been used previously to a very limited extent and then only for their mechanical and chemical characteristics rather than for their optical properties. We were thus dealing with a completely unexplored material, at least in the optical sense, and work was therefore directed towards characterizing the glass. Just as its physical properties and their difference from those of silica are important to the fabrication process, a comparison of the optical properties of the two materials is equally significant in propagation studies. The parameters of particular interest are the compositional variation of refractive index relative to that of silica, and the dependence of the index on wavelength. The former is required to enable the fibre to be tailored to a given refractive-index profile and numerical aperture, while the latter has a profound effect on pulse propagation, as will become apparent.

While it proved possible to determine the compositional index variation by numerical aperture measurements (see P3.5), the wavelength variation of the index proves more difficult. In bulk samples of glass it is relatively simple to measure the refractive index n at various wavelengths λ , using for example an Abbé refractometer. Thus both the first and second derivative of the index with wavelength may be obtained. The first derivative $dn/d\lambda$ determines the 'profile dispersion' and affects the form of the index profile required for optical group delay equalisation between modes (see reference 1 for an explanation of profile dispersion). We are concerned here with the second derivative $d^2n/d\lambda^2$, which is important when the fibre is used with sources having a relatively broad spectral spread. It determines the transit time differences which exist between the various spectral components of the input source. A pulse having a finite spectral width propagating in a dispersive medium becomes broadened in time as a result of the wavelength dependence of the refractive index and thus of the group velocity.

The various spectral components of the pulse arrive at the output at different times, and this is known as material (or chromatic) dispersion.

Unfortunately it is extremely difficult to prepare bulk samples of phosphosilicate glass in order to measure its index. Phosphorus pentoxide has a high vapour pressure and evaporates from the glass during the melting stage unless high pressures are applied. Furthermore, it is not unlikely that the properties of the glass in the fibre differ considerably from those in bulk, owing to the severe thermal shock of the fibre-drawing process.

An experiment which allowed these difficulties to be overcome is described in publication P7.1. Measurements of the chromatic dispersion of phosphosilicate glass were achieved in the fibre itself by injecting pulses of various wavelengths and observing their relative propagation delay. After being generated by Raman shifting a ruby laser, the pulses were transmitted through lengths of up to 1km of phosphosilicate fibre having various P_2O_5 concentrations and radial index profiles. By this means the spectral dependence of group delay was measured, from which $d^2n/d\lambda^2$ could be calculated.

7.2 Discussion

The results provided confirmation of what had already been suspected, namely that the material dispersion of phosphosilicate glass is virtually identical to that of pure silica. The chromatic dispersion of a material is determined largely by the strong absorption caused by electronic transitions sited in the ultra-violet portion of the spectrum. It could reasonably be inferred, therefore, that since the spectral attenuation of phosphosilicate glass is similar to that of silica, its chromatic dispersion would also be unchanged. In contrast, a germania-silica glass has both a higher absorption in the blue region of the spectrum and a larger material dispersion.

The experiment indicated that the addition of phosphorus pentoxide to silica in no way compromises the excellent optical characteristics of the material. Since silica possesses the lowest chromatic dispersion of all common glasses, this conclusion is of some importance as it permits a high bandwidth to be obtained with broad-linewidth sources such as light-emitting diodes. Furthermore, no measurable dependence of the chromatic dispersion on phosphorus pentoxide content could be found, thus providing additional confirmation that the binary glass has a value similar to that of silica. This may be compared with the only other measurement made to date on a fibre core material, namely the germania/silica binary glass. The value obtained at Bell Telephone Laboratories[2] for this system was limited by the measurement technique to only one wavelength, 900nm, but indicated an increase of nearly 50% over the figure for pure silica.

The measurements reported in P7.1 constitute the only thorough investigation yet conducted of the material dispersion characteristics of the core of an optical waveguide. A particular strength of the technique developed for the measurement is that it enables results to be obtained over a broad wavelength range. This is critically important when a comparison is to be made between the characteristics of a binary glass and those of the host material. Furthermore, as discussed in the following section, the nature of material dispersion is such that it becomes vanishingly small at some wavelength in the region 1.2-1.4μm, and it is obviously desirable to know the exact wavelength at which this occurs. Although our results do not extend to as long a wavelength as this owing to the inadequacies of the ruby laser source, the measurement technique is ideally suited to near-infra-red determinations. It is hoped to extend the measurements towards the wavelength of zero material dispersion in the future.

7.3 The Material Dispersion Limitation to Fibre Bandwidth (P7.2)

In publication P7.2 the implications of the results obtained in P7.1, and outlined above, are pursued further. The material dispersion of the fibre core material becomes the dominant factor in limiting the bandwidth of the guide once the group velocity differences are effectively equalised by grading the core refractive index. The limitation can be serious for a source having a broad spectral spread, such as an L.E.D., although it is not negligible even for the relatively narrow linewidth of a laser. This is clearly shown by curves 2a and 2b of publication P7.2, in which the fibre bandwidth per kilometre is plotted against wavelength of operation for several prospective sources. To take an example, a 1km graded-index fibre excited by an L.E.D.

operating at 0.9μm is limited to a transmission rate of just over 100Mb/sec by material dispersion. This is despite the fact that the waveguide dispersion alone would permit 2.5Gb/s.

The central purpose of publication P7.2 is to point out that an accessible wavelength region exists in phosphosilicate fibres at which the material dispersion vanishes and therefore can no longer significantly curtail the bandwidth. All glasses possess a similar zero in chromatic dispersion; the significance of the phosphosilicate result is that the zero occurs at a wavelength which is accessible in terms of the fibre attenuation. Publication P3.4 of Section I showed for the first time that in a phosphosilicate fibre with its characteristically low water content the attenuation in the vicinity of 1.3μm could be below 5dB/km. Thus provided the material dispersion of the core material is similar to that of silica and has a zero at 1.27μm, operation at the zero is possible. Most other glass systems have their material dispersion zero within a region of unacceptably high attenuation, usually between 1.3-1.4μm, and this effectively precludes its adoption.

As fibre losses become lower and lower, the presence of the accessible zero material dispersion region described in P7.2 assumes considerable importance. The achievement of lower losses is accompanied by an increase in projected repeater spacing, and consequently a greater demand is made on bandwidth per kilometre. The recent Japanese result[3] of 0.47dB/km at 1.25μm obtained with the phosphosilicate vapour-deposition technique suggests that repeater spacings of greater than 40km are feasible. In this case a modest system transmission rate of only 200Mb/sec demands an equivalent bit rate per kilometre of 8Gb/sec. The only means of achieving this at present is with a single-mode fibre operating at or near the material dispersion zero, which of course is also the spectral region in which the reported loss minimum occurs. The Japanese result is therefore significant both in emphasising the importance of the 1.3μm spectral region and in highlighting a growing reliance on single-mode fibres. Furthermore, the point made in P7.2 is all the more telling once it is appreciated that the loss minimum of 0.47dB/km in a phosphosilicate fibre is coincident with its zero in material dispersion. With such advantages available within this spectral region it would be surprising if means are not found to take advantage of them.

Publication P7.2 has played a not inconsiderable part in spurring activity towards the development of sources and detectors operating at longer wavelength (see for example reference 4). The revelation of the existence of a low-loss region near 1.3μm as a result of the ease with which the hydroxyl impurity may be eliminated from phosphosilicate glass has also apparently not gone unheeded. Although it is slightly irksome that the lowest loss yet reported[3] was obtained, not at Southampton, but at a Japanese laboratory, it is gratifying that the full potential of the phosphosilicate glass and fibre fabrication process should have been so dramatically realised.

References

1. Gloge, D., Kaminow, I.P. and Presby, H.M.:'Profile dispersion in multimode fibres: measurement and analysis', Electron. Lett., 1975, 11, pp 469-471.

2. Gloge, D., Chinnock, E.L. and Lee, T.P.:'GaAs twin-laser setup to measure mode and material dispersion in optical fibers', Appl. Opt., 1974, 13, pp 261-263.

3. Horiguchi, M. and Osanai, H.:'Spectral losses of low-OH-content optical fibres', Electron.Lett., 1976, 12, pp 310-312.

4. Mabbitt, A.W. and Goodfellow, R.C.:'High-radiance small-area gallium-indium-arsenide 1.06μm light-emitting diodes', Electron. Lett., 1975, 11, pp 274-275.

PUBLICATION P7.1

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: https://doi.org/10.1016/0030-4018(75)90164-9

PUBLICATION P7.2

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/el:19750135

CHAPTER 8

SINGLE-MODE FIBRE EVALUATION

8.1 The Single-mode Fibre (P8.1)

In the previous chapter it emerges that as the fibre loss diminishes the single-mode fibre becomes increasingly attractive for long-distance, high-capacity transmission. In view of this, it is surprising that very little work on the monomode fibre has been reported. Most work has been concentrated on multimode, graded-index fibres, largely because of their less critical jointing tolerances compared to those of the monomode fibre. Nevertheless, a recent paper[1] suggests that the single-mode fibre is less susceptible to the excess attenuation produced by microbending and therefore should be considerably easier to cable. Together with the ease and speed of fabrication, this could outweigh the difficulty of splicing and make the monomode fibre economically attractive.

Single-mode fibres having a phosphosilicate core are made in much the same way as the multimode fibres described in Chapter 3. A brief description of the fabrication method is given in P3.5 and section 3.6 of Chapter 3. Since only a single layer of phosphosilicate glass is deposited, the process is much quicker than that for a multimode fibre. Furthermore, the dispersion properties of the fibre are not critically dependent on the index profile, as in the graded-index fibre, provided single-mode operation is maintained. This considerably eases the fabrication process. However, since the core diameter is typically only 3-6μm it is not easy to achieve a closely-controlled, predetermined core size and thus ensure that no higher mode propagation is permitted. In addition, the depletion by vaporisation of the phosphorus pentoxide from the centre of the tube during the collapse process leaves the core refractive index and profile in some doubt. Routine measurements of the fibre parameters are therefore required to provide information which will allow small corrections to be made to the fabrication process and permit a particular fibre specification to be attained. For example, until better control is achieved it is often necessary to pull a short test length of fibre to evaluate the waveguide parameters. The remainder of the preform may then be drawn to a diameter which yields the required propagation characteristics.

Clearly there is a demand for a rapid, convenient method of determining the parameters of a single-mode fibre. Existing methods were unsatisfactory since they were tedious and inaccurate. For example it was often necessary to measure the fibre core diameter in a scanning electron microscope. A new method which avoids the previous difficulties and satisfies all the requirements is described in publication P8.1.

8.2 Fibre Measurements (P8.1)

The procedure outlined in P8.1 is unique in that it allows the unambiguous and simultaneous measurement of both the core diameter and the refractive-index difference. It relies on the fact that the far-field radiation angle of the HE_{11} mode is related to the normalised frequency V of the fibre; therefore a measurement of the half-intensity width of the radiation pattern allows a determination of V. Unfortunately this in itself is insufficient for most purposes, since V is a function of (i) the core diameter a and (ii) the index difference Δn. Thus a further measurement of either (i) or (ii) is required to fully specify the fibre. Although this can be provided by tedious methods such as etching the core, it was discovered that a far more convenient means is to observe the side lobes of the radiation pattern. The angle of the first minimum in the radiation field provides the required additional measurement and determines both a and Δn. The method has proved both accurate and easy to use. Results of determinations made on various fibres may be found in the paper, together with a more detailed description of its use.

A simple observation of the far-field pattern is therefore all that is required to specify a single-mode fibre completely. The technique is now regularly used in our laboratories and, because of its simplicity, will quite possibly be adopted eventually as the standard test method for all monomode fibres. It thus forms a valuable contribution to the growing field of optical fibre measurement techniques.

References

1. Petermann, K.:'Microbending loss in monomode fibres', Electron. Lett., 1976, 12, pp 107-109.

PUBLICATION P8.1

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/ij-moa:19760002

SECTION III

GRADED-INDEX FIBRES

CHAPTER 9

TUNNELLING LEAKY MODES IN GRADED-INDEX FIBRES

9.1 Introduction

The final Section of this thesis is concerned with some of the properties of graded-index fibres and particularly with the propagation of leaky modes in parabolic-index fibres. Chronologically the work stems from observations made during the development of a novel and convenient means of measuring the fibre refractive-index profile. However, it will not be presented in this order, since it may be more readily followed if the basic theory is given first. Thus the experiments which initiated the project will not be described until the following chapter. It may nevertheless be instructive to recall that the ultimate objective of the theory is a method for determining the index profile of a fibre by observation of the intensity distribution across its end face (the 'near field'). Currently this remains the central objective, although the development of the theory has served to highlight the importance of leaky modes in graded fibres. In particular, it was not previously recognised that modes of this type can have a considerable effect on measurements of fibre attenuation, pulse dispersion and splice loss.

The work to be described was performed in conjunction with M.J.Adams and F.M.E.Sladen.

9.2 The Acceptance Angle of Leaky Modes in Graded-Index Fibres (P9.1)

The existence of tunnelling leaky modes in step-index fibres and the effect they have on propagation characteristics is well-known from the extensive work of A.W.Snyder (see for example, reference 1).

To use ray terminology, he has shown that in a fibre with a homogeneous core a tunnelling leaky ray is one of the class of skew rays which are allowed by a purely geometrical optics analysis to propagate at an angle greater than the meridionally-defined numerical aperture. Whereas these rays do indeed propagate, in reality they do so with a degree of radiation loss. In mode terminology, a tunnelling leaky mode is one which is below cut-off, but which still maintains a large proportion of its energy trapped within the core. Although the mode must radiate since it is below cut-off, the loss may be relatively small and the mode may therefore persist for considerable distances. The term 'tunnelling leaky mode' was coined in analogy with quantum mechanical tunnelling. The electromagnetic wave 'tunnels' from the core/cladding interface (in a step-index fibre) to emerge at some radius in the cladding, from which it radiates. The transmitted wave appears to originate from this 'caustic', having 'tunnelled' from the core through a radially evanescent field region. Tunnelling arises because the wave is unable to follow the curved interface without its phase-velocity exceeding the velocity of light in the cladding. The point at which this occurs is the radiation caustic.

Although leaky modes in step-index fibres were well characterized, it was not generally appreciated that they also exist in graded-index fibres. In retrospect, however, there seems little reason to believe that they should not. Nevertheless, nothing was known about their number, attenuation, or propagation characteristics. Our discovery of leaky modes in a parabolic-index fibre resulted from a persistent error which occurred in the near-field scanning technique for index-profile determination (Chapter 10). This led us to develop a theory which allowed a description of the modes. The analysis which evolved is given in publication P9.1. It extends the tunnelling mode concepts, which previously had been applied only to step-index fibres, to include fibres having an arbitrary circularly-symmetric index profile.

The analysis has its foundations in the now classic work of Gloge and Marcatili[2] in which the WKB method is employed to predict the performance of fully-excited graded-index fibres. Their theory is based on bound mode propagation only and assumes that once a mode is below cut-off it may be ignored. This is equivalent to the assumption that no ray may be accepted by the fibre once it has an angle to the axis greater than the local numerical aperture. Since leaky modes are disregarded, their results underestimate the power carried by the waveguide for all but very long fibre lengths.

Our analysis represents an analytical extension of their work to include modes below cut-off, since these will almost invariably be present. By using a transition from modes to rays, we have defined an angular region in which leaky rays may be found in any index profile. This concept of an angular acceptance region is a particularly useful one in understanding the characteristics of leaky-mode propagation. The main conclusions of the analysis may be summarised as follows.

i) Tunnelling leaky modes may propagate in all circularly-symmetric optical fibres. Their number and the power they carry depends on the profile; in general both are greatest for the step-index fibre.

ii) A leaky ray in a graded-index fibre may be defined as one which propagates at an angle greater than the local numerical aperture and further, is one which would be predicted by geometrical optics to be trapped. In contrast to the step-index fibre, the local numerical aperture in a graded-index fibre depends upon the radial position on the fibre end-face and varies from a maximum at the centre to zero at the core/cladding interface. Note that the term 'graded-index' is used here to mean a profile having a maximum on axis and a smooth gradation to a constant lower value in the cladding.

iii) The angular region in which leaky rays may be launched lies outside the local acceptance cone of the bound rays. Whereas the acceptance cone for bound rays is circular, that of the leaky rays is elliptical, having a major axis at right angles to the radial direction. Reference to publication P11.1, Chapter 11, will clarify the geometry of the various acceptance regions for the special case of a parabolic-index fibre.

iv) In a parabolic-index fibre the acceptance region for leaky rays always lies within the angular limits of the meridionally-defined numerical aperture.

This last result is perhaps the most significant of all, since it has widespread implications for measurements on parabolic-index fibres, as follows. In the step-index fibre little attention need be paid to tunnelling modes, as they are all found outside the fibre numerical aperture. They are therefore rarely excited, since it is usual to arrange the source so that its angular aperture corresponds to that of the fibre. This is not the case in a parabolic-index fibre. Any multimode source arranged to fill the meridional numerical aperture will excite some, if not all, of the tunnelling leaky modes, and they must therefore be taken into account in fibre measurements.

9.3 Discussion

We may conclude that tunnelling leaky modes are of considerably greater importance in graded-index fibres than in step-index fibres, simply because it is difficult to avoid launching them. For example, the conventional excitation source for spectral attenuation measurement is a tungsten-halogen lamp, focussed through a lens of similar numerical aperture to that of the fibre. If the radiation completely fills the end-face, it will efficiently excite the complete set of leaky modes in a parabolic-index fibre, but none at all in a step-index fibre. Since the attenuation is determined by comparing the output from a long length of fibre to that from a short length, it is hardly surprising that researchers had previously observed with some puzzlement that a graded-index fibre always appears to possess a decibel or so higher loss than a step-index fibre. The measurement, of course, includes the loss of the leaky modes since they are present and are recorded in the output from the short length, but have largely radiated away, and are therefore not recorded, in the long length.

A further indication of the effect of leaky mode propagation is given in P9.1, Fig.3. The curves show the near-field intensity distribution, for various index profiles, found by summing the power contained in both bound and leaky modes. The near-field exhibits a substantial departure from that previously predicted[2] using the assumption that only bound modes propagate in the fibre. This has a profound effect on the near-field scanning technique for index-profile determination (Chapter 10).

In addition to the errors in attenuation measurements, it is readily seen that other fibre measurements may be equally affected. This is particularly true of measurements which use short lengths of fibre, such as the determination of splice loss (Chapter 11). Another measurement which will possibly be influenced is pulse dispersion; this is treated in the following section.

9.4 The Effect of Leaky-mode Propagation on Pulse Dispersion (P9.2)

Further properties of tunnelling leaky modes in graded-index fibres are given in publication P9.2. The paper deals largely with the propagation delay of the leaky modes and the effect they have on the pulse dispersion. It is also concerned, however, with the number of leaky modes which exist in a parabolic-index fibre and delineates their range of propagation constants.

Perhaps the most significant result given in P9.2 is that there are $V^2/12$ leaky modes in a parabolic-index fibre, where V is the normalised frequency. Since the bound modes total $V^2/4$, 25% of the power is launched into the leaky modes if all modes are equally excited. This compares with 50% for a step-index fibre. The above result has subsequently been confirmed by several authors (see references 3 and 4 for example). Although less than for a step-index fibre, the power carried by leaky modes is by no means insignificant in a parabolic-index fibre, and can be expected to strongly influence measurements.

A further conclusion which may be drawn from P9.2 is that the transit times of leaky modes are always greater than that for bound modes in fibres having a profile parameter α greater than $2-2\Delta$, where Δ is the maximum relative index difference (see reference 2 for definitions of α and Δ). Thus the presence of leaky modes at the output of these fibres will add a 'tail' to the pulse. It is however possible to eliminate the increase in pulse width by choosing a profile having $\alpha = 2-4\Delta$.

Profiles having α between $2-2\Delta$ and $2-4\Delta$ are unique in that they equalise the transit times of the leaky modes to lie partly or wholly within the range observed for the bound modes. Thus the bound mode transit times and those of the leaky modes overlap to a degree which depends on the choice of profile. When $\alpha = 2-4\Delta$ the overlap is complete and all leaky modes arrive within the same time period as the bound modes. The pulse width is therefore a minimum. A further decrease in α will result in some of the leaky modes arriving before the fastest bound mode, and a degradation of the leading edge of the pulse will result.

9.5 Leaky, Bound and Refracted Modes

The two publications presented in this chapter assume that leaky modes are a clearly identifiable class of mode and that they propagate unattenuated. The assumption is necessary at this stage in order to describe more clearly the properties of the modes. A worst-case estimate of the effects of leaky modes results since, in reality, the loss of the leaky modes is finite. So far we have assumed that all bound modes and leaky modes find their way to the fibre output, while modes launched outside the angular region delineating bound and leaky modes (refracted modes) are immediately lost.

In practice the distinction between the three classes of modes is not so clear. Theoretically we define a bound mode as one with oscillating field behaviour within the core of the waveguide and an exponential decay (evanescent) behaviour everywhere else. It thus possesses no radially-directed propagation constant within the cladding and has no radiation loss. A refracted mode has exponentially-growing, oscillatory radial field behaviour throughout the cladding and is therefore not localised, i.e. trapped, within the core. It radiates from the core/cladding interface and is lost within a very short length. A leaky mode, on the other hand, lies between these two extremes; it possesses oscillatory fields within the core and is bounded by evanescent field conditions within the cladding, just as is a trapped mode. However, at some radial distance from the core/cladding interface the field becomes radially periodic once more. The mode radiates from this point, which is known as the outer radiation caustic.

To summarise, a bound mode does not radiate; it may be thought of as having an outer radiation caustic at infinity,where the field has decayed to zero. A refracted mode radiates from the core/cladding interface and therefore has a caustic equal to the core radius. Intermediate between these two lies the leaky mode which, depending on the mode under consideration, radiates from some radius between the core/cladding interface and infinity.

The distinctions between the modes, although clear in theory, are somewhat artificial in practice, particularly when the added complication of a finite cladding width is taken into account[5]. The loss of the set of leaky modes varies between zero for the least leaky, to virtually infinite for the most leaky. They may therefore be regarded as having characteristics which grade smoothly between those of bound and those of refracted modes. Thus, whereas it is not accurate to assume that the number of modes propagating in the fibre is clearly delimited by the cut-off of the highest mode, as in reference 2, it is equally inaccurate to delimit the number of modes by the synthetic boundary between leaky and refracted modes, as we have done. Nevertheless, publications P9.1 and P9.2 serve to draw attention to the existence of leaky modes in graded-index fibres and to define the circumstances under which they may be launched. The following chapter completes the picture by including the attenuation of leaky modes, thereby giving an indication of their practical significance.

References

1. Snyder, A.W.:'Leaky-ray theory of optical waveguides of circular cross section', Appl. Phys., 1974, 4, pp 273-298.

2. Gloge, D. and Marcatili, E.A.J.:'Multimode theory of graded-core fibers', Bell Syst. Tech. J., 1973, 52, pp 1563-1578.

3. Someda, C.G. and Zoboli, M.:'Illumination of graded-core fibres', Electron. Lett., 1975. 11, pp 577-587.

4. Love, J.D. and Pask, C.:'Universal curves for power attenuation in ideal multimode fibres', Electron. Lett., 1976, 12, pp 254-255.

5. Stewart, W.J.:'Leaky modes in graded fibres', Electron. Lett., 1975, 11, pp 321-322.

PUBLICATION P9.1

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/el:19750180

PUBLICATION P9.2

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/el:19750295

CHAPTER 10

THE NEAR-FIELD SCANNING TECHNIQUE FOR INDEX-PROFILE DETERMINATION

10.1 Measurement of Index Profiles (P10.1)

The great strength of the homogeneous CVD technique is its ability to produce fibres having virtually any form of refractive-index profile. Thus, as one of the originators of the production process we were faced with the problem of determining the index profiles of the wide variety of fibres that could thereby be produced. Rapid and accurate measurements are required to provide information on the conformity, or otherwise, of the index profile to the ideal near-parabolic form. Existing methods were few and suffered from being either inaccurate or tedious. Of the available methods, the most commonly used is the interference technique[1], which requires a thin cross-sectional slice to be cut from the fibre. The slice is polished and placed in an interference microscope. Concentric-ring interference fringes are generated by the difference in optical path lengths seen by the light as it traverses regions of varying refractive index. The spacing of the fringes gives a measure of the index profile.

Apart from the inconvenience and difficulty of polishing the slice, the method suffers from several disadvantages. The most serious of these is caused by the curvature of the image field which results from the focussing action of the sample. The slice is effectively a tiny lens having a focal length comparable to its thickness. This produces a field distortion such that the image of the fringes is not localised in a plane,but forms a spherical image surface. Since the high-power microscope objectives which are required to observe the fibre core have a limited depth of focus, it is not possible to view the whole of the image simultaneously and the complete fringe field cannot be recorded. The only way to reduce the effect is to decrease the focal length of the slice by reducing its thickness. Unfortunately a thinner slice displays fewer interference fringes across the core; a typical CVD fibre slice with a sufficiently long focal length may only exhibit 3 fringes,from which the entire index profile must be inferred. Obviously the spatial resolution available is very poor and makes the method ill-suited to observations of small-scale imperfections caused, for example, by the layer structure of CVD fibres. The technique will effectively average all small-scale imperfections in the profile.

Although the smoothing yields a more aesthetically pleasing result, the apparent perfection of the profile is often a delusion, particularly with regard to one of the most interesting features of fibres produced by CVD, the central dip. The interference method is unable to resolve the full extent of the dip in refractive index at the core centre caused by the evaporation of the P_2O_5 additive from the inside layer in the tube during the high-temperature collapse process. The latter has only become apparent as a result of the development of the near-field scanning technique described here.

Despite its inconvenience and poor resolution, the interference method has been extensively used in other laboratories and many examples may be found in the literature of the reassuring index profiles obtained. Nevertheless, it was largely the inconvenience of the method and not its poor resolution which led to our development of a new method, the near-field scanning (NFS) technique. The idea stems from the routine observation of the fibre end-face in a microscope, when it was noticed that if the fibre was illuminated from the far end the intensity variation across the core appeared to correlate with the index profile. In addition, Gloge and Marcatili[2] had previously demonstrated theoretically that the intensity distribution and the index profile are identical, provided all modes are equally excited. Early experiments in our laboratories showed this to be substantially true and led eventually to a far simpler and more satisfactory means of measuring the refractive-index profile than the interference method. The experimental technique was first reported in publication P10.1, where details of the apparatus and the results obtained may be found. Briefly, a short length of fibre is illuminated from the far end by an incoherent source such as a tungsten lamp and the index profile determined by observation of the light intensity variation across the fibre output face (the near field). The following points serve to emphasise some of the features of the method.

1) We have verified that the near-field intensity distribution closely resembles the refractive-index profile and can therefore be used as a method of measurement, provided all modes are equally excited. Although it does not appear to have been fully appreciated[3], the latter condition is critical to the measurement. It may be achieved by using a source having

a Lambertian (cosine) angular intensity distribution, for example a light emitting diode (LED) or a tungsten lamp. If the condition is not met, the near-field distribution will modulate with fibre length. For instance, in a parabolic-index fibre the source distribution will be periodically reproduced at intervals along the fibre,since the fibre has imaging properties.

2) In common with our earlier work on step-index fibres (Chapter 4), the theory of Gloge and Marcatili does not include the effects of mode coupling or differential modal attenuation. These must therefore be avoided by measuring the near-field intensity distribution on a short length of fibre, i.e. a few metres. The theoretical assumptions impose several other conditions which must be met for the experiment to yield accurate results. They are concerned with the validity of ray optics and are similar to those outlined in Section II of this thesis.

3) The NFS method very rapidly yields the refractive index profile with a minimum of sample preparation. The fine detail which may be observed is excellent and far superior to that obtainable by other means.

4) As will be appreciated from the theory developed in the previous chapter, the presence of leaky modes in graded-index fibres is unavoidable, particularly in the short lengths of fibre that we are constrained to use for the measurement. In addition it was shown that leaky-mode propagation influences the near-field intensity distribution; consequently it no longer accurately reflects the refractive-index profile. A length-dependent error results, the magnitude of which depends on the power remaining in leaky modes at the fibre output. The inaccuracy will depend on the fibre parameters;for example, it will be relatively trivial for small-core fibres having a low V-number,in which leaky mode attenuation is high. The form of the error is such that a smoothly increasing departure from the correct value occurs with increasing radius.

5) The existence of an error which smoothly affects the general form of the profile suggests that the interference and NFS methods of profile determination are complementary. The former yields the general form of the profile, but cannot show the detail, and vice versa. Thus is is possible to exper-

imentally generate a specific correction factor for subsequent NFS measurements by comparing a single interference observation with a near-field plot. The correction obtained in this way may be used to allow for the effects of leaky modes on subsequent samples of fibre having similar, but not necessarily identical, profiles. This is perfectly satisfactory for a production test facility, where the fibre parameters would not depart greatly from the original standard fibre. In general, however, the required correction will depend on the characteristics of the fibre under test.

Ideally a calculated correction factor, which may be adjusted to the fibre under test, is required. The correction must take into account the attenuation of leaky modes in fibres having a range of possible index profiles, core diameters, numerical apertures and lengths. Only in this way is it possible to predict the residual leaky-mode contribution to the near-field. Publication P10.1 shows such a correction in use and compares the index profile obtained by the NFS technique with that obtained by the interference method. The agreement is excellent and confirms the validity of the correction employed. The following section gives details of the derivation of the correction.

10.2 Computation of the Universal Correction Factors (P10.2)

The necessity for a correction factor detracts a little from the versatility of the NFS technique. It is clear that the convenience of the method makes it particularly suited to production quality control and indeed, at present, it is the only contender for this application. As such it has been extensively adopted (see for example reference 4) regardless of the error which is known to exist. The development of a convenient form of correction would therefore render the method even more attractive. In principle, it is possible to calculate the precise index profile from a knowledge of the numerical aperture, core radius, length and near-field distribution. However, an individual computation for each fibre is highly inconvenient and makes the method unattractive. On the other hand, if the correction factors can be normalised in such a way as to require only one set of curves to describe a variety of fibres, the computation effort becomes minimal and the accuracy of the NFS technique is considerably improved.

Publication P10.2 is concerned with the calculation of the losses of leaky modes in fibres having arbitrary refractive index profiles. It outlines the evolution of a universal set of correction curves which may be used to account for the existence of leaky modes in the near-field and to convert intensity distribution measurements into accurate refractive-index profiles. The procedure to determine such a correction factor is as follows. We first calculate the attenuation coefficient of each leaky mode from a 'tunnelling coefficient', found by application of the WKB method. The accurate near-field distribution may then be obtained by summation of the power remaining in all modes after a given length of fibre. The result will lie between that of Gloge and Marcatili[2], which did not recognise the existence of leaky mode propagation, and that of publication P9.1, which assumed that all leaky modes were present unattenuated. A comparison of the true length-dependent near-field with the refractive-index profile will then indicate the magnitude of the correction which it is necessary to apply. Details of the calculation may be found in publication P10.2, together with the implications of the presence of leaky modes for attenuation measurements.

P10.2 is particularly concerned with the development of analytic approximations which will allow the normalisation of the correction factors into a convenient universal form. Although, in general, the attenuation of the leaky modes depends on the index distribution, it is clear that a correction factor which requires prior knowledge of the form of the profile being measured is highly unsatisfactory. Consequently we seek analytic approximations which remove the dependence on profile and therefore allow the correction to be applied to any fibre. The approximations used are as follows.

a) The outer turning point (caustic) of a ray propagating in the core of a graded-index fibre is assumed to be at the core/cladding interface. In practice, of course, rays may have outer caustics at any radial distance from the core centre. However, we are only interested in the least leaky modes, as these will contribute most to the near-field. In this case the assumption is a reasonable one, since these rays do indeed have caustics near the interface.

b) The distance between successive approaches of a ray to its of leaky-mode attenuation and this unfortunately depends strongly on the form of the profile. A coarse approximation must be made here, as for all but the parabolic-index fibre the ray period depends on the ray under consideration. An average value is therefore taken to cover the rather wide range of periods found in fibres described by the same numerical aperture and core diameter, but which differ in index profile. Full details of these approximations may be found in both P10.2 and in the following publication,P10.3.

10.3 Results

1) With the aid of the above analytic approximations,it is possible to calculate the required correction factors and to normalise them by a single parameter X which depends only on the fibre length, numerical aperture and core radius. Thus a single set of curves may be generated to cover a wide range of possible fibre characteristics and profiles, considerably simplifying the application of the correction.

2) The use of the curves results in a considerable improvement in the accuracy of the NFS technique, as shown by Figs. 3 and 4 of publication P10.1. Note that the fibres used in the experiments require a particularly large correction. A typical fibre produced by CVD requires a smaller correction, as it has a lower X-value. Consequently,the departure of the near-field from the index profile may be relatively small. Nevertheless, for accurate measurements a correction is required.

3) The necessity for a correction factor cannot be avoided by the use of longer lengths of fibre, as has been suggested. The length required would be several hundred metres and other propagation effects would then dominate the results.

4) The analysis in publication P10.2 also includes the length dependence of the total power remaining in leaky modes. It may be seen that the power is not negligible after a length of one kilometre for a typical parabolic-index fibre. This has particular significance for the measurement of the fibre attenuation, as outlined earlier. For example, if an attenuation measurement is carried out with a Lambertian source on a 100m fibre, using a 50cm reference length, the presence of leaky modes leads to an apparent excess loss of 1.3dB/km.

5) The ordering of the correction factors into a convenient and usable form requires the application of some rather coarse approximations. Although the validity of the approximations has been demonstrated experimentally,both in the case of a step-index and a parabolic-index fibre, it remains to verify the performance of the correction over a wider range of fibres. In particular,verification for high X-values is needed, as these are commonly encountered in CVD fibres. The following section and publication P10.3 are concerned with further computations to this end.

10.4 Numerical Computation of the Correction Factors (P10.3)

The investigation of the range of validity of the approximations (a) and (b) above takes the form of numerical computations of the correction factor for a range of profiles, described[5] by a profile exponent g of 1.5, 2, 3, 4 and ∞ . The analytic approximations made previously are avoided by using the more accurate form of the tunnelling coefficient T (for definitions see P10.2). The integration is performed numerically for each mode. The ray period is obtained more precisely for each ray in a given profile by utilising an approximation due to Gloge[5]. In this way an accurate correction is obtained which is applicable to a particular profile only. Fortunately it is found that the results may still be normalised by the X-value given previously and thus may be conveniently compared.

The results of the above exercise are given in P10.3, Fig.1, and may be summarised as follows.

1) Our previous assumption that the correction factor would be approximately independent of profile is verified. The correction required for fibres having a given X-value and a range of profiles is remarkably similar up to a normalised core radius of 0.8. Fortunately,the departures which occur at greater radius are acceptable, at least in graded-index fibres which have a small index difference at the radius where the correction-factor errors are largest. This may be seen as follows:-

We define[5] the profile error E as the ratio of the maximum deviation dn from the true profile n(r), to the index difference at the core centre:

$$E = \frac{dn}{n_o \Delta} \quad (1)$$

where
$$\Delta = \frac{n_o - n_2}{n_o}$$

and n_o, n_2 are the refractive indices at the core centre and the core/cladding interface.

If P(O) and P(r) are the intensities measured at the core centre and at radius r respectively, we infer the index profile from (see P10.1)

$$\frac{n(r)-n_2}{n(O)-n_2} \simeq \frac{P(r)}{P(O)} \cdot \frac{1}{C(r,z)} \quad (2)$$

where C(r,z) is the correction factor. It may easily be shown that if the correction factor C(r,z) contains a percentage inaccuracy δ then

$$E = \frac{P(r)}{P(O)} \; \frac{\delta}{C(r,z)} \; \% \quad (3)$$

For a parabolic index fibre of core radius a, the error is given by

$$E \simeq (1-\rho^2)\delta$$

where $\rho = r/a$ is the normalised radius. Thus an error in correction factor of 8% at a normalised radius of 0.85 produces a profile error of only ∿2%, which is an acceptable value[5]. An inaccuracy of this magnitude would hardly be visible in the corrected plot.

Thus the errors inherent in the use of a generalised correction factor are tolerable in that they conveniently occur at a large radius. This of course is not the case for step-index fibres or for fibres having high index exponents. In practice, the NFS technique is normally used for determinations of index exponents in the range 1.5 to 4.

2) The more-accurate numerical computations, whilst confirming the similarity which exists for different profiles, indicate that the approximations made previously become increasingly inaccurate as the fibre X-value becomes larger. The effect may be seen by a comparison between Fig.3 of P10.2 and Fig.3 of P10.3. The analytically-derived corrections are somewhat too small as a result of the two approximations producing an error of similar sign. A numerically-derived curve is

therefore preferable. It should be noted, however, that while the difference in the correction factors calculated by the two methods appears quite large, the effect on the inferred index profiles is small, since the corrections themselves are small for all but fibres of low X-value.

3) It is clear that a single set of correction factors may be applied to a range of different fibres, as originally surmised. However, it is perhaps too ambitious to suggest that the curves will serve every possible fibre. For example, considerable errors would result if a curve computed for a parabolic-index fibre were used to correct a step-index fibre. Nevertheless, the curves can be used for a surprisingly large range of profiles without incurring a significant error. Since the range of accuracy of the curves encompasses the fibres normally of interest, the restrictions on their use are of minor importance.

Recent improvements in the CVD manufacturing process have changed the emphasis from the determination of arbitrary profiles to one of measurement of closely-controlled near-parabolic profiles. In this case it is preferable to use a correction curve calculated specifically for a parabolic-index fibre. Publication P10.3 gives such a set of curves.

10.5 Discussion

At present the NFS technique provides the only viable alternative to the interference method for index profile determination. In addition, it is considerably more convenient and provides a higher resolution of fine detail in the profile. It should, however, be emphasised that the limitations of the method are yet to be fully determined. Ideally the accuracy of the method should be tested by comparing a series of measurements of widely different index profiles with those found by a method of reliable accuracy. Unfortunately such a method does not exist; there appears to be little to choose between the accuracy of the NFS technique and the interference method. The limited comparisons made to date between the two suggest that the agreement is good. However, for experimental convenience the fibres were always chosen to have large core diameters and numerical apertures, and thus a large V-value. Since the assumption of a mode continuum is explicit in the theory presented earlier, it is not inconceivable that the theory would be more generally applicable to fibres having large V. Certainly preliminary experiments on fibres having small V-values, i.e. less than 20, show considerable departures both from the bound mode theory of Gloge and Marcatili and from the leaky mode extension presented here. Thus it is dangerous to judge the general applicability of the method on the excellent agreement obtained with high V-value fibres. Work is at present continuing on verification of the technique for fibres having V-values in the range 20-40.

Experimentally some care must be taken to ensure that no additional loss of the leaky modes occurs. It is found that both tight bending of the fibre, and excessive pressure, produced for example by end clamps, can effectively strip some of the leaky modes from the fibre and reduce the accuracy of the experiment. It would be ideal if all leaky modes could be stripped in this way and the need for a correction factor obviated. Unfortunately this is not possible, as some of the bound modes are also invariably stripped by the deliberate introduction of kinks in the fibre. We are left therefore with no alternative but to ensure that the leaky modes do not suffer excess loss and to correct the profile for their presence. No doubt reports[6] of accurate results obtained without the use of a correction are a result of a fortuitous balance between the excess loss of bound modes and the power remaining in leaky modes.

It has been found experimentally that both the thickness and loss of the fibre cladding can cause excess attenuation of leaky modes. The effect of cladding loss is not unexpected, as the proportion of leaky-mode power which propagates in the cladding is high. The thickness of the cladding, on the other hand, influences the result only if it is such that the mode fields extend significantly through the cladding into the medium surrounding the fibre. The theory assumes that the core is imbedded in an infinite, uniform cladding medium and this assumption is invalidated once the cladding thickness is less than about 50% of the core radius. Fortunately neither the requirement for a low-loss cladding nor for one of adequate thickness proves particularly restrictive. Most CVD fibres possess the required characteristics.

A further and less clearly understood excess loss has been found in fibres which exhibit departures from circularity in the core. Although slight ellipticity of the core appears to have negligible effect on the measurement, a small geometrical imperfection can very effectively discriminate against leaky modes. The imperfections which prove most damaging are those which have a tight local radius of curvature, such as an angular protrusion of the core into the cladding. Since this is uncommon in well-made fibres it is not regarded as a major disadvantage.

In summary, a systematic evaluation of the limitations of the NFS technique is under way. Preliminary results suggest that the restrictions on the general applicability of the method are not serious, but should be recognised by the user. It is probable that all optical methods of profile determination will be similarly limited,since ultimately the inaccuracies can be traced to the size of the specimen relative to the wavelength of light. It is also worth recalling that an accurate knowledge of the profile is required only to predict the pulse performance of the waveguide. Since the pulse dispersion is very sensitive to the form of the profile, direct measurements of pulse performance provide the conclusive test of profile accuracy.

<u>References</u>

1. Stone, J. and Burrus, C.A.:'Focusing effects in interferometric analysis of graded-index optical fibres', Appl. Opt., 1975, <u>14</u>, pp 151-155.

2. Gloge, D. and Marcatili, E.A.J.:'Multimode theory of graded-core fibers', Bell Syst. Tech. J., 1973, <u>52</u>, pp 1563-1578.

3. Someda, C.G. and Zoboli, M.:'Illumination of graded-core fibres', Electron. Lett., 1975, <u>11</u> pp 577-587.

4. Olshansky, R. and Keck, D.B.:'Pulse broadening in graded-index optical fibres', Appl. Opt., 1976, <u>15</u>, pp 483-491.

5. Gloge, D.:'Propagation effects in optical fibers', IEEE Trans. Microwave Theory Tech., 1975, <u>MTT-23</u>, pp 160-120.

6. Maurer, R.D.:'Fibers for ten kilometer-one hundred megabit per second transmission', First European Conf. on Optical Fibre Communication, London, Sept. 1975.

PUBLICATION P10.1

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: https://doi.org/10.1063/1.88729

PUBLICATION P10.2

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: https://doi.org/10.1016/0030-4018(76)90215-7

PUBLICATION P10.3

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: 10.1049/el:19760218

CHAPTER 11

SPLICING TOLERANCES IN GRADED-INDEX FIBRES

11.1 Calculation of Splice Loss (P11.1)

It was shown in Chapter 9 that tunnelling leaky modes in parabolic-index fibres are all contained within the limits of the meridionally-defined numerical aperture. Consequently modes of this type assume a greater importance in graded-index fibres than in step-index fibres, where they are rarely excited. The implications for the measurement of fibre attenuation have already been investigated. The present chapter is concerned with a further implication, namely the excitation of leaky modes at splice imperfections and the effect this has on the apparent joint loss.

An imperfect fibre splice results in a redistribution of power amongst the modes of the waveguide. Frequently the new mode spectrum has a higher overall loss than that before the splice, caused, for example, by excitation of higher-order modes which are subject to higher modal attenuation. Thus a spatial transient follows the splice as the power within the modes decays and redistributes to a form which minimises the overall loss. Measurements of splice loss made within the spatial transient region will yield an optimistic result.

A principal cause of such a spatial transient in graded-index fibres is the excitation of leaky modes. This is not the case for a splice between two step-index fibres, as we have already seen that all leaky rays are found in an angular region outside the numerical aperture. They therefore cannot be excited by a simple lateral displacement at a butt joint. On the other hand, the smallest misalignment between graded-index fibres produces a mismatch between the emission angle of one fibre and the acceptance angle of the other, since the local numerical aperture is a function of radius. Clearly this will excite tunnelling leaky modes in the receiving fibre.

The imperfections which are possible at a junction between two fibres are numerous. They include effects which are avoidable in principle,such as the inclusion of dirt between the end-faces and inadequate flatness of the fibre ends. We are concerned here with imperfections which are always present to a degree, namely the small misalignments which exist between two fibres. Of the three possibilities, angular misalignment, end-face separation and transverse misalignment, the latter shortcoming is the most difficult to avoid. The assumption will therefore be made that the only misalignment present is transverse. Further assumptions are that the two fibres are identical in both core radius and numerical aperture and that the emitting fibre is fully excited.

Details of the calculation of the splicing loss between both step-index fibres and parabolic-index fibres is given in publication P11.1. As usual, the solution to the problem involves the assumption of a mode continuum. This permits the use of geometrical optics and allows us to use the concept of local acceptance regions. The jointing efficiency may then be found by calculating the overlap of the emitting fibre radiation cone with the local acceptance cone of the receiving fibre, followed by a summation of the overlap over the common core area. For the step-index fibre the solution simply involves a calculation of the overlap area, since the local acceptance angle for bound modes is constant over the end-face.

The excitation of leaky modes in the receiving fibre is included by defining an angular acceptance region in which they may be launched. In a practical case we are not interested in the limits of acceptance of all leaky rays, since many of these will radiate very rapidly. We therefore delineate an angular acceptance region in which only low-loss leaky modes are launched. In this way an effective local numerical aperture can be defined to include the acceptance angle of the bound modes and that of the persistent leaky modes. If the effective local numerical aperture is now used to calculate the angular overlap between emitting-fibre radiation cone and receiving-fibre acceptance cone at a point on the fibre end-face, the results will include the effect of leaky-mode excitation. The length dependence of the residual power in tunnelling modes is implicit in the calculation, as the magnitude of the effective receiving local numerical aperture will depend on the length specified after the splice.

The details of the calculations given in P11.1 provide considerable insight into the properties of leaky modes in parabolic-index fibres. Fig.1 is particularly illuminating as it clearly delineates the various angular acceptance regions. It also serves to emphasise the distinction between leaky modes which have low loss,and those which radiate within a short distance of the source and therefore are of little importance. We see that the total acceptance angle of leaky modes is largely of academic interest,since the effective acceptance angle for the example given is not very much greater than the bound mode acceptance angle. Nevertheless,the difference is sufficient to cause appreciable errors in the NFS technique

11.2 Results

The calculation of splice loss as a function of lateral misalignment covers two cases of importance:

a) The receiving fibre is long so that the leaky-mode spatial transient has subsided. The attenuation measured under these conditions may be regarded as the 'true' splice loss, since it is the figure which has greatest practical significance.

b) The receiving fibre is short so that measurements are made within the spatial transient regime. Reported[1,2] measurements have frequently been made under these conditions.

The results are summarised as follows.

1) When the receiving fibre is long, a junction between step-index fibres is more tolerant to misalignment than an equivalent parabolic-index fibre splice. Typically a 100μm core-diameter parabolic-index fibre requires alignment to better than 6.4μm to achieve a splice loss of 0.5dB. The loss for the same misalignment between step-index fibres is about 25% lower. Fortunately the tolerances needed to splice parabolic-index fibres are not unacceptably greater than for the step-index fibre,and do not therefore represent a serious disadvantage.

2) Measurements made on graded-index fibres within the spatial transient regime will be optimistic. Under certain conditions, for example a measurement made within a metre or so of a splice, the underestimation may be such that the parabolic-index fibre appears more tolerant to misalignment than a step-index fibre. Care must therefore be exercised to ensure that the spatial transient has subsided before measurements are made. It may be necessary to allow a hundred or so metres after the splice before accurate measurements are obtained.

This requirement has not been appreciated in previously published work on jointing loss.

3) Clearly, a succession of closely-spaced splices will not produce an additive loss. In this case the assumption of only bound mode excitation in the emitting fibre, used in the present work, is no longer valid. The individual splice loss will depend on the emitting fibre mode spectrum, which in turn will depend on the misalignments found in the previous slice.

11.3 Conclusions

The results given here represent the first attempt to put the splicing losses experienced between graded-index fibres on a quantitative basis. The analysis provides several useful conclusions, not least of which is the unexpectedly small difference in splicing tolerance between step and graded fibres. Before the publication of this work it had even been suggested that a graded-index fibre would be as difficult to joint as a single-mode fibre.

It should be emphasised that the calculated results will probably overestimate the loss in a practical field splice. In this case the fibres will be partially rather than fully excited, as a result of mode filtering. The spatial transient is then caused both by leaky-mode and by higher bound-mode excitation. Both will decay after the splice with their own characteristic attenuation. It is probable, however, that the results presented here will still provide a reasonable first-order description.

References

1. Miller, C.M.:'Loose tube splices for optical fibers', Bell Syst. Tech. J., 1975, 54, pp 1215-1225.

2. Yohanzadeh, Y.:'Hot splices of optical waveguide fibres', Appl. Opt., 1976, 15, pp 793-795.

PUBLICATION P11.1

The following published papers were included in the bound thesis. These have not been digitised due to copyright restrictions, but the links are provided.

DOI: https://doi.org/10.1063/1.88842

CONCLUSIONS

It is clear from the work presented here that dramatic progress has been made in the technology of optical waveguides. The initial expectations for the attainable fibre attenuation and bandwidth have both been greatly exceeded. The fibre loss has been reduced from several thousand dB/km to less than one dB/km. Few physicists would have dared to predict that a solid material could be so transparent. It is interesting to observe that the purity of the phosphosilicate glass made by the homogeneous CVD process is such that it has a loss similar to that of the atmosphere on a clear day in a mountain region, when a typical visibility of 30km prevails. In both cases the optical transmission is limited largely by scattering.

Similarly, the low mode-mixing which exists in the fibres reported here is remarkable. We have shown that the perfection of the liquid-core waveguide is such that a single mode may be transmitted over several hundred metres, even though the fibre is capable of supporting some 8000 modes. This is equivalent to obtaining single-mode propagation in a 100GHz H_{01} millimetre waveguide, some 30cm in diameter and 3000km long! By virtue of the highly-stable pulling process, it clearly proves easier to make a near-perfect waveguide at optical frequencies than at millimetre wave frequencies.

The work presented in this thesis has concentrated on the optical transmission medium; it has shown the technical feasibility of high-capacity fibre optical communication systems. The desired transmission objectives have largely been met by the development of the phosphosilicate fibre, while a much clearer understanding of fibre propagation has resulted from the work described in Section II.

However, there are a number of other requirements which have to be met before fibres may be regarded as a practical communications alternative to the present copper-based systems. T-junctions, splices, demountable connectors and terminations are just a few examples of the associated components which have yet to be developed. Moreover, considerable research is required into fibre strength and cable design. Investigations in these areas are continuing in our own laboratories and elsewhere.

PUBLICATIONS INDEX

P1.1 Relaxation processes in glasses as shown by optical attenuation experiments
F.F.Y.Wang, J.P.Dakin, D.N.Payne and W.A.Gambling, Journal of Non-Crystalline Solids. 14,pp 48-53, 1974.

P1.2 The preparation of multimode glass- and liquid-core optical fibres
D.N.Payne and W.A.Gambling, Opto-Electronics 5, pp 297-307, 1973.

* * *

P2.1 New low-loss liquid-core fibre waveguide
D.N.Payne and W.A.Gambling, Electronics Letters 8, pp 374-6, 1972.

* * *

P3.1 A resistance-heated high temperature furnace for drawing silica-based fibers for optical communications
D.N.Payne and W.A.Gambling, American Ceramic Society Bulletin 55, pp 195-197, 1976.

P3.2 A new silica-based low-loss optical fibre waveguide
D.N.Payne and W.A.Gambling, Electronics Letters 10, pp289-290, 1974.

P3.3 The preparation of water-free silica-based optical fibre waveguide
D.N.Payne and W.A.Gambling, Electronics Letters 10, pp 335-336, 1974.

P3.4 A borosilicate-cladded phosphosilicate-core optical fibre
D.N.Payne and W.A.Gambling, Optics Communications 13, pp 422-425, 1975.

P3.5 Optical fibres based on phosphosilicate glass
W.A.Gambling, D.N.Payne, C.R.Hammond and S.R.Norman, Proceedings IEE. 123, pp 570-575, 1976.

* * *

P4.1 Launching into glass-fibre optical waveguide
J.P.Dakin, W.A.Gambling, D.N.Payne and H.Sunak, Optics Communications 4, pp 354-7, 1972.

P4.2 Pulse dispersion in glass fibres
W.A.Gambling, D.N.Payne and H.Sunak, Electronics Letters 7, p 549, 1971.

P4.3 Propagation model for multimode optical-fibre waveguide
W.A.Gambling, J.P.Dakin, D.N.Payne and H.R.D.Sunak, Electronics Letters 8, pp 260-2, 1972.

P4.4 Theory of dispersion in lossless multimode optical fibres
J.P.Dakin, W.A.Gambling, H.Matsumura, D.N.Payne and H.R.D.Sunak, Optics Communications 7, pp 1-5, 1973.

P4.5 Novel mode filter for use with cladded-glass and liquid-core optical waveguide
W.A.Gambling, J.P.Dakin, D.N.Payne and H.R.D.Sunak, Electronics Letters 8, pp 262-3, 1972.

* * *

P5.1 Dispersion in low-loss liquid-core optical fibres
W.A.Gambling, D.N.Payne and H.Matsumura, Electronics Letters, 8, pp 568-9, 1972.

P5.2 Gigahertz bandwidths in multimode, liquid-core, optical fibre waveguide
W.A.Gambling, D.N.Payne and H. Matsumura, Optics Communications 6, pp 317-322, 1972.

P5.3 Effect of loss on propagation in multimode fibres
W.A.Gambling, D.N.Payne and H.Matsumura, Electronics Letters 9, pp 412-414, 1973.

P5.4 Determination of mode conversion coefficients in optical fibres
W.A.Gambling, D.N.Payne and H.Matsumura, Applied Optics 14, pp 1538-1542, 1975.

P5.5 Optical fibres and the Goos-Hanchen shift
W.A.Gambling, D.N.Payne, H.Matsumura and M.J.Medlicott, Electronics Letters 10, pp 99-101, 1974.

* * *

P6.1 Mode excitation in a multimode optical-fibre waveguide
W.A.Gambling, D.N.Payne and H.Matsumura, Electronics Letters 9, pp 412-414, 1973.

P6.2 Propagation in curved multimode cladded fibres
W.A.Gambling, D.N.Payne and H.Matsumura, AGARD Conf. on Electromagnetic Wave Propagation involving Irregular Surfaces and Inhomogeneous Media, March 1974, The Hague.

P6.3 Pulse dispersion for single-mode operation of multimode cladded optical fibres
W.A.Gambling, D.N.Payne and H.Matsumura, Electronics Letters 10, pp 148-149, 1974.

* * *

P7.1 Evaluation of material dispersion in low-loss phosphosilicate- core optical fibres
B.Luther-Davies, D.N.Payne and W.A.Gambling, Optics Communications 13, pp 84-88, January 1975.

P7.2 Zero material dispersion in optical fibres
D.N.Payne and W.A.Gambling, Electronics Letters 11, pp 176-178, 1975.

* * *

P8.1 Determination of core diameter and refractive index difference of single mode fibres by observation of the far-field pattern
W.A.Gambling, D.N.Payne and H.Matsumura, IEE J. MOA., 1, 1976.

* * *

P9.1 Leaky rays on optical fibres of arbitrary (circularly symmetric) index profiles
M.J.Adams, D.N.Payne and F.M.E.Sladen, Electronics Letters 11, pp 238-240, 1975.

P9.2 Mode transit times in near-parabolic index optical fibres
M.J.Adams, D.N.Payne and F.M.E.Sladen, Electronics Letters 11, pp 289-391 , 1975.

* * *

P10.1 Determination of optical fiber refractive index profiles by a near-field scanning technique
F.M.E.Sladen, D.N.Payne and M.J.Adams, Applied Physics Letters 28, pp 255-258, 1976.

P10.2 Length dependent effects due to leaky modes on multimode graded-index optical fibres
M.J.Adams, D.N.Payne and F.M.E.Sladen
Optics Communications 17, pp 204-9, 1976.

P10.3 Correction factors for the determination of optical fibre refractive-index profiles by the near-field scanning technique
M.J.Adams, D.N.Payne and F.M.E.Sladen, Electronics Letters 12, pp 281-283, 1976.

* * *

P11.1 Splicing tolerances in graded-index fibres
M.J.Adams, D.N.Payne and F.M.E.Sladen, Applied Physics Letters 28, pp 524-526, 1976.

* * *