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Optical fibres: the Southampton scene

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Abstract: Southampton University was one of the first to carry out research into optical fibres. The paper summarises why research started at Southampton, the direction it took and some of its successes, and finishes with some speculations about the future.

1 Precursor

The writing of an historical account of the development of a subject is fraught with difficulty. One is inevitably drawn to the conclusion that it is only possible to describe the sequence of events from a largely personal viewpoint since this is how one sees the situation at the time and, to a greater or lesser degree, subsequently. This article therefore attempts to outline how the urge to initiate research into optical fibres for signal transmission arose at the University of Southampton, how particular research directions were chosen, some of the principal successes, and ends with some speculations about the future.

A question which the author has frequently been asked is how the idea of taking up research on optical fibres arose in the first place and whether it was an accidental quirk of fate. The truth is rather less romantic. After eight years investigating hydrogen arc plasmas at the Universities of Liverpool and British Columbia, I came to Southampton (and this really was a fortuitous accident but that is another story) and became interested in active devices for pushing the frontiers of electronic communication to even higher frequencies. A study of noise in the (then) conventional backward-wave electron beam oscillator led on to the new semiconductor diode parametric, and tunnel diode, oscillators. I also took an active interest in the construction of the first British ammonia maser oscillator in a parallel project in the Department under D.J.E. Ingram (now Vice-Chancellor at the University of Kent). On the departure of Dr. Ingram to a chair at Keele I collaborated with Dr. T.H. Wilmshurst on the use of the ammonia maser as a 24 GHz amplifier for electron spin resonance spectroscopy. Thus began a research programme on quantum electronic devices which ultimately led to a separate research group being formed.

2 The initial scenario

The most spectacular development in quantum electronics was the report of the first laser operation in 1960. Then followed a massive outpouring of results from many parts of the world as new laser materials and configurations were rapidly discovered. Laser research was also undertaken in the Department at Southampton, in collaboration with Dr. (later Professor) R.C. Smith (now Director of Kingston Polytechnic) who jointed us from Harvard University as a research fellow. The purpose of this research was to try and develop laser devices suitable for application as carrier sources in communications.

The attraction of moving to higher carrier frequencies is, of course, that the bandwidth, or channel capacity, available from a communication system is, very approximately, proportional to the operating frequency. Thus microwave systems are limited to bandwidths of a few tens of megahertz, whereas with optical waves it should be possible to improve the capacity by a few orders of magnitude. At the same time, past experience indicated that the transmission cost per circuit mile would probably be greatly reduced.

Whilst this research was underway consideration was given to the very necessary question of what kind of transmission path might be suitable at optical frequencies. Line-of-sight propagation at ground level, the obvious candidate, is obviously susceptible to bad weather. Even in relatively good conditions temporal and spatial variations in temperature can cause an initially collimated beam to break up and become unstable. For example, a temperature difference of 0.001 K across a light beam 10 cm wide and 1 km long is sufficient to deflect it by a distance equal its own diameter. It was estimated that the maximum distance over which it is possible to obtain 99% reliability of transmission under all weather conditions is only a few kilometres — clearly not an attractive commercial proposition whatever the bandwidth.

Protection from atmospheric fluctuations could, in principle, be provided by enclosing the light beam in a protective pipe. However, to avoid a large increase in loss and multipath dispersion, caused by reflections at the inner wall, the pipe would have to be of large diameter, and to be laid in an optically straight line of course. Not a very convenient method of linking the centre of London with the centre of Birmingham. Consideration was given [1] to lining the pipe with a smooth, highly reflecting material which would reduce the losses but not the dispersion. Another suggestion [2] was to counteract beam spreading by introducing a periodic sequence of weakly converging lenses into the pipe. A considerable amount of work was done on such beam guiding systems at the, then, Bell Telephone Laboratories, USA, including the development of thermal lenses [3] to avoid loss at the surfaces of hard lenses, but it was clear that the beam waveguide would either have to be evacuated or extensively thermally isolated. An experimental length of 1 km, laid above ground, had an experimentally measured loss of 1 dB/km, but only for a short period in the middle of the night when the surrounding thermal atmosphere was relatively stable. The view was taken at Southampton that such a waveguide was not an economic practical proposition and no work was undertaken on it.

3 The optical fibre

The problem therefore remained as to how modulated light could be guided over long distances. One other method which was known at the time involved the use of a cladded glass fibre consisting of a cylindrical core surrounded by a cladding of lower refractive index. The ability of a transparent dielectric rod to guide light by

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total internal reflection had been known for a long time; but the existence of an evanescent field at the surface, together with the inevitable deterioration of the surface in the atmosphere, rendered the device impracticable. A much more recent advance [4] had been the concept of surrounding the guiding rod with a second material, which had to be of lower refractive index to retain the possibility of total internal reflection, thereby protecting the reflecting surface and providing a shielded region for the evanescent field. The two materials, core and cladding, had to be physically and chemically compatible and capable of being drawn down to a small diameter if the structure were to have any degree of flexibility. Such cladded glass fibres had been fabricated and made up into bundles to provide flexible light guidance in medical endoscopes. However, the attenuation of the fibres was so high that propagation was only possible over distances of a metre or two, whilst the strength was so poor that normal handling of the bundles would cause breakage of individual fibres to a noticeable degree. They were therefore totally unsuitable for long-distance transmission.

Nevertheless, some thought was being given to the potential use of optical fibres [5, 6]. For example, in an address to the British Association for the Advancement of Science at Southampton in 1964 I discussed existing work on unguided propagation and beam waveguides and went on to speculate about the potential applicability of optical fibres. I recall being questioned closely on the practicalities by the Director of Research of the (then) Post Office. However, serious interest was not aroused until the publication of the now famous paper [7] of Kao and Hockham in 1966. This paper was important in two major respects. First, it showed that one candidate optical fibre material, namely silica, might perhaps be capable of a transmission loss at visible wavelengths potentially low enough for telecommunication purposes. Secondly, it aroused sufficient interest among funding bodies for three research programmes to be supported. In addition to Kao's work at STL, Harlow, a group was established at the British Post Office Research Station, Dollis Hill, together with a joint research programme between the Signals Research and Development Establishment, Christchurch, Dorset, and my own group in the Electronics Department at Southampton University.

4 Starting from scratch

The SRDE/Southampton work, funded by the Ministry of Defence, began in October 1966 to carry out a research feasibility study of a cheap, low bandwidth, optical fibre communications system suitable for distances of several kilometres. The target was thus slightly different from that of the groups at STL and BPO, who were aiming at the longest possible distance and maximum bandwidth. For our purpose multimode fibres would probably be sufficient, rather than the single-mode requirement of STL and BPO. It was decided that research on transmitters, receivers, components and the system should be done at SRDE, while the University would study bulk glass and fibre properties and fibre fabrication techniques. Whilst in the University group there was considerable experience in microwave and laser techniques, no-one had any knowledge of glass, nor the faintest idea of how to make fibres. Nothing daunted, the first research fellow was appointed, Dr. (now Professor) P.J.R. Laybourn, and a theoretical study of propagation in fibres begun. Experimental work was not to begin for another year because the contract supporting the research, whilst agreed in principle in early 1966, was not to provide any hard cash until January 1968, and the author was on sabbatical leave in the USA during the academic year 1966/67.

The next stage was to find out what an optical fibre really was by attempting to make one. The standard method at the time was the 'rod-in-tube' technique, whereby one takes a rod of core glass, places it inside a tube of cladding glass, and the composite is placed in a vertical furnace with a short hot zone and drawn down into a fibre. Since we knew nothing about furnaces or fibre drawing, it seemed sensible to approach one of the major glass companies in the UK to seek help and advice. This we did and received neither. The only help we could get was from a friendly electronics company who showed us their technique for drawing short rods into longer ones in the preparation of fibre-optic faceplates. In addition, the writer had seen precision-bore glass tubing being drawn for travelling-wave tube devices. This paucity of knowledge and assistance turned out to be a blessing in disguise, because not knowing what parameters were the critical ones the decision was taken to control everything to the highest degree possible within a tall rigid structure. The wire-wound drawing furnace had precise control of temperature (better than 0.1°C) up to 1200°C and of drawing speed (0.1%). The fibre drawing equipment was designed and constructed by Dr. D.N. Payne, who had joined the research group as a research student (and now is Pirelli Reader in Optical Fibres), and the success of the design may be judged from the fact that this fibre drawing tower is still in everyday use.

At the same time equipment for the measurement of transmission loss and scattering loss in bulk glasses was being set up by another research student, Dr. J.P. Dakin. The difficulties here were considerable, in that the transmission losses being measured were tiny compared with end reflections on the samples and variations in transmitted intensity caused by inhomogeneities. Nevertheless, after much hard work, some successful double-beam spectrophotometers were constructed [8] at both Southampton and STL, and classical measurements demonstrating the Rayleigh nature of scattering in bulk, high-quality, optical glasses were carried out.

5 The first measurements

Measurements on commercially available optical fibre bundles indicated transmission losses of several thousand dB per kilometre. After a study of likely starting materials, most of the early fibre fabrication was carried out with Schott F7 rods as core glass and Pilkington ME1 tubing as cladding. The first fibres drawn had an encouraging loss of about 1000 dB/km and, after a careful study of drawing conditions, this was reduced to 400 dB/km. At the time, about 1968, the author recalls with wry amusement being warmly congratulated on this result by R.B. Dyott of the Post Office Research Station. How times have changed! Further studies, including fibre annealing, brought the loss down to 150 dB/km, which corresponded to that being measured on the bulk starting rods. This result, whilst archaic now, demonstrated that the effects of waveguide inhomogeneities could be reduced to a low level, at least compared with this magnitude of loss. Measurements of light scatter, together with its dependence on scattering angle, confirmed the Rayleigh mechanism and that the loss value was extremely small.

As well as studying fibre fabrication and the measurement of materials parameters, we were also studying the potential bandwidth of our multimode fibres. This was expected to be small, as, if all possible modes were excited in the fibres, the large spread in group velocities would limit the bandwidth to 10 or 20 MHz over one kilometre. However we produced subnanosecond pulses by mode locking a helium/neon laser and were able to show [9] that, even in step-index multimode fibres, very much larger bandwidths are possible. This later culminated in the measurement of a bandwidth x length product in a liquid-cored fibre of 1 GHz km over a length of about a kilometre [10], although this capacity was easily reduced if mode conversion was allowed to occur.

6 The pace quickens

In the years up to 1970 there were not many laboratories worldwide studying optical-fibre transmission. In particular, there had been a deafening silence from Bell Telephone Laboratories. The reason for this was explained to me by Rudi Kompfner some years later and after his retirement from Bell Laboratories. He said he was in charge of optical communications research at the time and his materials experts had informed him that it would not be possible to reduce material losses to the level required for long-distance transmission. They therefore persevered with the work on the beam-guiding system. However in the late 1960s he had a visitor from the UK who pointed out the progress that was being made here and, said Kompfer, 'work on optical fibres started at Bell Laboratories the next day'! Interest was quickened much more strongly in 1970 with the report [11] of a single-mode fibre loss of 20 dB/km. No indication was given as to how it was done, or what materials had been used.

At Southampton we were feeling frustrated at being limited to commercially available starting materials and could not afford the expensive equipment required to study the double-crucible method of fibre fabrication being developed at the Post Office Research Station. We had a collaborative programme with Professor H. Rawson at the University of Sheffield where preforms were being produced, from a double-layered melt, which we then drew into fibre. By this technique we were able to produce short lengths of fibre with 40 dB/km loss and a numerical aperture of 0.43, but the rate of supply of preforms was very limited. In 1971 news reached us of the liquid-core silica-cladding fibre developed in Australia* [12] and we immediately saw this as a method of obtaining our own in-house fibre supply and of gaining some experience in measurements and handling of low-loss fibres. Not, at that time, having facilities for drawing silica tubing, requiring a drawing temperature of 2000 K, we searched for an alternative core/cladding combination, and found that excellent fibres could be made with hexachlorobuta-1,3-diene in ME1 soft-glass tubing [13]. Liquid-core fibres are probably the most perfect step-index fibres ever made, in the sense that the core/cladding boundary is obviously very sharp. At no time did we see this fibre as being suitable for practical installation, but it proved an excellent experimental tool and enabled us to carry out some very good fundamental work on fibres. We achieved [14] a transmission loss of below 5.6 dB/km (the best in the world for several years) and, as indicated above, a bandwidth x length product of 1 GHz km. In fact we claim that this fibre carried the first commercial television broadcast, in that a one-hour colour television broadcast was made by the BBC from The Royal Institution in London along a length of this fibre on the way to the transmitter.

* OGILVIE, G.J.: Comments made at Symposium on Optical Transmission, Imperial College, London, March 1972

The cladding glass of the liquid-cored fibre was estimated to have a transmission loss of approaching 10 000 dB/km, but, because of the high numerical aperture, the effect on the total transmission loss was small. This somewhat surprising result was confirmed by other experiments and by theoretical analysis [15] which showed that a balance between numerical aperture and cladding attenuation could filter out high-order modes in a multimode fibre and thus compensate, to some extent, for mode conversion.

7 Frenetic fabrication

The situation with regard to fibre attenuation in the early 1970s was as follows. Commercially available glasses prepared by conventional techniques were known to have high attenuation and were therefore not suitable. An attenuation of 20 dB/km had been reported from Corning Glass Works and was thought to be made by depositing a soot of tinania-doped silica on the inside of a silica tube which was subsequently fused and drawn into a fibre. Liquid-cored fibres had been made with attenuations of a few dB/km, but these were not attractive for practical application. For example, to fill a capillary tube of 100 μm internal diameter and 1 kilometre length took about four hours, even with a driving pressure of 1400 atmospheres. The filling time of a single-mode fibre would be four orders of magnitude greater.

For many years bulk silica had been made by flame hydrolysis, starting with silicon tetrachloride, and the intrinsic loss of silica was known to be small. Silicon tetrachloride is liquid at room temperature and can therefore be relatively easily purified by successive fractional distillation. However, the process of flame hydrolysis, whereby silicon tetrachloride vapour is oxidised by heating in an oxy-hydrogen flame, introduces excess water into the resultant glass, which produces large absorption peaks in the wavelength region of interest. Many laboratories were tackling the problem of fibre fabrication, and the competition to produce the required breakthrough was intense. It was also known, but perhaps not widely appreciated by the potential fibre fabricators, that glass was being produced in microcircuit fabrication by a form of chemical vapour deposition in which the glass oxide was produced by oxidisation of the associated chloride. This was a heterogeneous process operating at low temperature with an extremely low rate of deposition totally inadequate for fibre fabrication.

Fibres had been drawn [16] from rods of silica coated with a boric oxide/silica glass layer and, more recently, with a modified core material apparently comprising a mixture of silica and germania [17]. It should be pointed out that the addition of titania or germania to silica raises the refractive index, whilst boric oxide has the reverse effect.

At Southampton we repeated the silica core/borosilicate cladding technique and found the numerical aperture was quite small. We sought a method by which core and cladding materials could be deposited at a high rate whilst avoiding the use of flame hydrolysis and the associated high water content. We achieved success in 1974 with a technique [18] in which a homogeneous vapour-phase reaction takes place inside a substrate tube, and the subsequent fine soot deposition is simultaneously fused into a clear glass layer. The resulting fibre comprised a new core material (as far as optical fibres were concerned) of phosphosilicate glass with a pure silica cladding region. This result was announced in the Electro-Optics Conference in

Brighton during the discussion of a paper from STL [19] on a germanosilicate core/silica cladding fibre. We claimed that our fabrication technique was novel, comprising homogeneous chemical vapour deposition and simultaneous fusing of the deposited layers. The phosphosilicate core composition was also novel and was found to have very low loss, very low scattering and was much cheaper than either germania or silica doping. In addition, the measured transmission loss was lower than had been predicted [20] for pure silica!

Word of our success reached Bell Telephone Laboratories where a similar process had been devised which they called 'modified chemical vapour deposition', a term which is now generally used. They knew that our work had been submitted for publication and therefore pulled out all the stops to get their work into print [21] in *Bell System Technical Journal.* We were subsequently told (unofficially) that this was done in the record time of two weeks, and a reading of these papers indicates that they were obviously put together in a very great hurry. The homogeneous/modified chemical vapour deposition process rapidly became, and remains, the one most widely used throughout the world. Through further development of this, and other, fabrication techniques, fibre losses have now reached astonishingly low levels of a few tenths of a decibel per kilometre, giving rise to transmission distances without repeaters of several hundred kilometres.

8 Single-mode or multimode?

As indicated earlier in this article, when optical fibre work began in the UK the efforts of the Post Office Research Station and STL were directed towards single-mode propagation, whereas the Southampton/SRDE research explored the possibilities of multimode transmission. The latter work soon demonstrated that multimode fibres could have bandwidth x length products approaching 1 GHz km if mode conversion could be avoided, or compensated, by mode filtering or mode scrambling. A better approach, however, was to introduce a graded refractive-index distribution into the core of the multimode fibre to reduce intermode dispersion.

A graded-index distribution had been produced in the well-known Selfoc fibre [22] developed in Japan in the late 1960s. Theoretically, it was shown subsequently that the appropriate refractive-index distribution should reduce the intermode dispersion, and therefore increase the bandwidth, by some three orders of magnitude over that in a step-index fibre, to about 20 GHz km. In practice, the great difficulty in producing a sufficiently accurate profile limited the bandwidth x length product to a few GHz km. Because of the problems with single-mode fibres, most research worldwide had now shifted to the multimode fibre. The advantages of multimode fibres were seen to include the larger core diameter, making jointing and launching rather easier than in a single-mode fibre which would have a core diameter of only about 5 μm.

In the early days of multimode fibres, the only method of measuring the refractive-index distribution in the fibre was to cut out a thin slice of a few micrometers in thickness which had to be polished optically flat on both sides. The slice was then inserted in an interference microscope and the radial variation in optical thickness measured. This method was time consuming and expensive to carry out and totally unsuitable for routine industrial use. We therefore devised the near-field scanning [23] technique which became widely accepted. As a result of further study of the process, the considerable significance of leaky modes was discovered and extensively analysed [24].

In the middle 1970s it became clear to us at Southampton that the profile problems in multimode fibres were unlikely to be solved satisfactorily, with the result that multimode fibres would be expensive to manufacture and the results of mode mixing, especially in concatenated fibre lengths, would be very difficult to control. We therefore turned our attention to single-mode fibres, and the original roles were now neatly reversed in that we were about the only major group not working on multimode fibres. Single-mode fibres are easier, and therefore cheaper, to manufacture, in that less material has to be deposited and, to a first approximation, slight variations in refractive-index profile along the length of the fibre are nowhere near as critical as in multimode fibres.

We first made some single-mode fibres with the MCVD technique to convince ourselves that there was no great problem. The refractive-index distribution could not be obtained by the near-field scanning method, but a new process [25], based on far-field measurements, enabled the core diameter and index difference of an equivalent step-index fibre to be determined. We then carried out theoretical and experimental work on losses induced by bends [26] and the mechanical alignments necessary at joints [27] in order to achieve low joint losses. These studies showed that the problems were not insuperable, and this has been borne out by subsequent work carried out elsewhere.

We then turned our attention to the question of dispersion in single-mode fibres. The dominant mechanisms were clearly material dispersion, related to the variation of group velocity with wavelength in the bulk material, and waveguide dispersion, i.e. the variation of group velocity with wavelength caused by the fibre geometry. A technique was developed [28] for assessing material dispersion through the dependence of group delay on wavelength. The measurements showed that the material dispersion was indeed close to that calculated for pure silica. The measurements were carried out at wavelengths below 1 μm, since, at that time, all fibre work was carried out with gallium arsenide sources operating at 0.85 to 0.9 μm. Our work indicated that the material dispersion would fall to zero at a wavelength of 1.3 μm, and this was an extremely important result because it showed that the effects of material dispersion could be eliminated by moving operation to this wavelength. In fact, calculations showed that in multimode fibres a move from 0.85 to 1.3 μm would increase the bandwidth available by an order of magnitude with both semiconductor laser and light-emitting diode sources. As a consequence of this, and the fact that the attenuation was found to be 0.4 dB/km compared with 2 dB/km at 0.85 μm, attention worldwide shifted rapidly to the longer wavelength, and work was initiated to develop suitable sources.

Having removed both intermode and material dispersion, the next important parameter was waveguide dispersion. Because material dispersion passes through zero at 1.3 μm, it transpires that the material and waveguide dispersions become opposite in sign at longer wavelengths, and, in another important result, we were able to show [29] that, by appropriate fibre design, it is possible to make the combined effects of material dispersion, mode dispersion and profile dispersion add to zero at any chosen wavelength from 1.3 μm up to 2 μm or so. This was a markedly simple result, which had a profound effect on single-mode fibre design, and is a technique followed in the fabrication of all single-mode fibres for large bandwidth applications. In particular, the attenuation has a minimum at a wavelength of 1.55 μm of about 0.2 dB/km, and in the so-called 'waveguide-shifted' fibres the fibre design is such that the bandwidth is a maximum at the same wavelength where the loss is a minimum. Thus single-mode fibres can transmit over 200 km with a bit rate limited only by the speed at which the source can be modulated.

9 Present and future

From the middle 1970s onwards the number of laboratories taking up research, development and production of optical fibres increased very rapidly, and the output of papers reached avalanche proportions. It was clear that optical fibres were rapidly moving out of the research laboratories into widespread application, and they have now revolutionised long-distance telecommunications. The history of the subject from this point onwards, therefore, takes a different form and should be the subject of a separate article. All that needs to be said here is that glass fibres and photons are rapidly displacing copper wire and electrons in the telecommunication networks of most technologically advanced countries. For example British Telecom have ceased ordering coaxial cable for the trunk telephone network which will have well over half the traffic carried by optical fibres within five years from now. There is already strong penetration into the intermediate network, and detailed consideration is being given to the introduction of single-mode fibres into the local network and local-area networks. The first optical fibre underwater cables are being laid, and it will soon become possible, for the first time, to transmit television, as well as telephone, traffic across the Atlantic and other oceans by cable.

Even so, optical fibre communications is in a very crude state of development. We do not yet have coherent operating systems or circuit components, so that the optical sources are, in effect, optical noise generators, and all processing of the signal has to be carried out by transformation down to electronic frequencies. The wavelength window available in a single optical fibre is of the order 100 000 GHz, of which, so far, we can use not much more than 1 GHz. This situation will change rapidly in the next few years, with the result that optical fibres will transform long-distance, as well as short-distance, telecommunication transmission out of all recognition. The information revolution is well underway.

10 Acknowledgments

The author would like to pay tribute to many colleagues he has had the pleasure and privilege of working with over the years and without whom this story could not have been told. Many of them now hold senior positions in the optical fibre industry and elsewhere. It would be a difficult and invidious task to select individual names for mention and it is not possible to list them all. However, no-one will doubt that my senior colleague, Dr. D.N. Payne, Pirelli Reader in Optical Fibres, has made an outstanding contribution to the subject in general and to the Optical Fibre Group at Southampton in particular.

The work at Southampton would not have started when it did, nor developed as rapidly, without the encouragement and support of Mr. G. Phillips of the (then) Signals Research and Development Establishment, Christchurch, Dorset, who organised a generous research contract. Acknowledgment is also due to the generous award of research fellowships by the Pirelli General Cable Company which gave us an invaluable freedom of action.

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