In the beginning there was light

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1. Introduction

This paper presents a personal account of an engineer (the writer, who participated in the early stages of R&D) as he saw it and experienced it.

The early stages of optical communication research at Standard Telecommunication Laboratories (STL), Harlow, UK, was an exciting time, full of expectations of the things to come. A number of first rate researches made up the team, had the confidence that their efforts would not be in vain and that commercial success will only be a matter of time – somehow. This was a very happy period of my professional life: in retrospect, it was the combination of challenging technical problems and the first rate colleagues that made it so.

In the story which follows we examine a number of decisions which culminated in STLs commitment to optical fibre communications and to the commercial success which followed.

2. The antecedents of optical communications

I am often asked who was the inventor of optical communications. The history has it that a whole series of events happened over hundreds of years and the eventual emergence of optical communications, and the optical fibre technology in particular, was a natural outcome. But, it was STL that made a serious commitment in the right direction and pointed the way for the rest of world to follow.

The beginnings of optical communications go back to antiquity. The earliest accounts of optical communication, using a courier-chain of fires go back to the fifth century BC. Such communication systems were designed to transmit a single encoded message, e.g., to signal the fall of a city in a war between two countries. In the same class we should put communication by smoke signal.

Semaphore (18th century) and the heliograph systems are representatives of a more sophisticated technology, in that they permitted transmission of an unlimited sequence of symbols (such as letters of alphabet) for sending complex messages over distances of hundreds of kilometres. Signalling using flags and naval shuttered signalling lamps (still used today) were later developments and belongs to the same class as the semaphore and the heliograph systems.

These early systems had, as we know, some very serious limitations, including unreliability (due to weather), inadequate capacity for carrying information and, of course, were characterised by high cost per bit of information transmitted. Furthermore, these systems belong to the class of "free space" communication systems. Like radio, they use free space as the medium of communication, but unlike radio, the waves associated with the visible part of the spectrum have a limited penetration capacity of most material objects and, therefore, fading problems are a much more serious limitation.

There are accounts of studies of light propagation along a jet of water as far back as 1820, and Graham Bell reported on experiments with transmission of speech signals along a light beam in 1880 [1]. The theory of propagation of electromagnetic waves along dielectric cylinders, the principle behind modern fibre-optic communication, was well established at the beginning of this century.

In this connection the pioneering work of Hondros [2] should be mentioned. Maxwells equations were discovered in 19th century and the mathematical tools were used by F. Harms at the beginning of this century to study electromagnetic wave propagation on dielectric cylinders. Harms also studied a range of modes which can propagate on dielectric cylinders. Among the modes which he discovered was the fundamental mode of propagation, the HE_{11}, which is the mode of propagation used with modern single mode optical fibres. With such a mode the energy flows in part within the dielectric cylinder and in part outside (in the form of surface wave).

The interest in surface waves was revived by G. Goubau in early 1950s [3]. Later on, Goubau studied "Beam Waveguides", an array of confocal lenses (see Fig. 1), intended for long distance communication by infrared or light beams. Goubaus ideas were soon followed up by Bell Laboratories in USA and by STL in England.

The first practical realisation of an optical cable made up of a multiplicity of glass fibres, each about as thick as human hair, is attributed to John Logie Baird (in 1927). Cables made up from early fibres had a serious shortcoming on account of the leakage of the optical energy from the fibres to the surrounding medium. The problem was eventually overcome by jacketing the individual fibres using a medium of a lower refractive index. In this way, the energy is confined to the core region by total internal reflection (with the associated evanescent field confined to the cladding). This was an important step forward which has helped to make modern optical communication possible. Yet at this stage of history we were a long way off the realisation of long distance guided optical communications because of lack of good optical transmitters and receivers.

The discovery of lasers in 1960 [4] stimulated the imagination of many and provided further encouragement, to some, to venture into guided optical communications.

Radio waves can also be guided by means of suitable cables and waveguides, as it is done with telephony and TV distribution networks. Most modern optical communication systems use optical fibre cables to guide the signal from source to destination. The idea is not new, but the technology is.

The history thus shows that free space optical communications, being in the form of "visual communications", e.g., smoke signals, or in the more recent realisations, e.g., semaphore, have been with us for many years. Work on guided optical communication has taken place largely in the last one hundred years. The following can be identified as the key events:

1. Theoretical and experimental studies of electromagnetic wave propagation on dielectric cylinders (Hondros and Harms);
2. The technology of cladded fibres;
3. The invention of solid state lasers;
4. The commitment of Standard Telecommunication Laboratories to optical fibre communications in early 1960s.

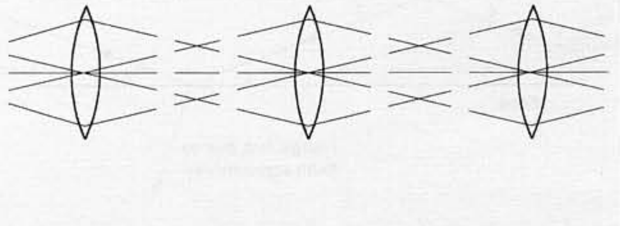

Fig. 1. Confocal lens system

3. The genesis of modern optical communications

In the account given below we examine a series of decisions which culminated in STLs commitment to optical fibre communications and to the commercial success which followed.

3.1. The events in the early 1960s

In an effort to provide for future needs in telecommunications a number of new initiatives were perused the 1950s. Among them, STL was engaged in a major research project on Trunk Waveguide Communication [5] using millimeter waves and the H01 mode of propagation. In UK STL was the first commercial organisation to work in this area and in the late 1905s field tests were carried out to examine the technical viability of the project. While it was acknowledged that much excellent technical work had been achieved, the commercial future was in doubt. Finally, by 1960 the research Trunk Waveguide Communication was phased out in **favour of a commitment to optical communications**.

In retrospect, we must acknowledge that this was an important decision, in that – while other major research laboratories continued research in Trunk Waveguide Communication even in the late 1960s – STL was able to concentrate its effort on optical communication from early 1960s. Moreover, it enabled STL to transfer research staff skilled in microwaves to R&D relating to optical communications: after all an optical fibre is only a particular embodiment of a waveguide. In long term, this management decision had an important beneficial effect on subsequent events and on the rate of progress in optical communications.

Consequent on these decisions a Division concerned with optical systems was formed. This was headed by Alex Reeves (the inventor of pulse code modulation) whose imagination, enthusiasm, and drive, had a lot to do with the success of the two teams under his leadership. It was Reeves who, already in late 1950s, argued that the future of communication lies in the domain of optics. He soon convinced me!

The research was organised in two groups: one concerned with electro-optic devices and the other with the communication medium and the related technologies (headed by the writer). It was the electro-optic group that produced, quite early on in history, solid state lasers alas of a rather short life, but sufficient to indicate the direction for future development. At this stage we could see light at the end of the tunnel.

The task for the communication group was already to study a range of alternative means of optical communications. Among others, we set up laboratory facilities for testing two classes of guiding structures, known at the time: (i) the reflecting pipe [6], and (ii) the beam waveguide, which used a confocal lens system, like the one shown in Fig. 1. In addition, free-space optical infrared communication was examined, as well as optical fibres.

A Progress Report concluded this phase of study. The report pointed to a limited potential for special applications of free space beamed transmission (e.g., among communication satellites). It also pointed to serious technical problems with confocal lens systems, on account of the necessary mechanical precision needed to set up the alignment of focusing elements and to maintain correct alignment in spite of earth movements due to seasonal or temperature changes.

As regards the guided transmission, two fundamental classes of waveguides has been studied in detail: Class 1 (reflecting pipe belongs to this class), where propagation takes place by reflection from the walls of the waveguide, as shown in Fig. 2, and Class 2 (optical fibres belongs to this class), where propagation takes place as a result of total internal reflection from the walls of the dielectric medium (Fig. 3). The conclusion of the study were then based on two key points:

- The losses in a Class 1 waveguide relate to imperfect reflection from the waveguide walls. These losses relate to fundamental properties of the materials from which the waveguide is made. But, since the physics teaches us that there is little we can do about it then the proper direction for research with reflecting pipes is clear: to reduce the attenuation we must make the ratio of the diameter of the reflecting pipe to the wavelength as large as practicable to reduce the ray angle θ (Fig. 2). Quartz tubes about 2 or 3 cm in diameter and silvered on the geometry of such tubes were prohibitive. To us, this was a clear hint to direct the research effort elsewhere.
- With Class 2 waveguide, the reflection from the walls of the waveguide is lossless. Here the losses, if any, must be due to the physical properties of the dielectric medium, such as absorption, or due to scattering from inhomogeneities in the glass. At the time, the experimental evidence indicated, for the best quality optical glass, an attenuation in excess of 1000 dB/km. Yet, theoretical studies indicated that Rayleigh scattering, due to frozen inhomogeneities in glass, could only account for less than 1% of the measured attenuation. This evidence seemed to indicate to us that the excessive losses must be due to minute impurities in the glass medium. However, the literature at the time did not provide adequate quantitative answers as to necessary degree of purity needed to secure a low attenuation.

4. The stage is set: the players move in

Having identified a limited commercial potential for free space optical communication and serious problems with beam waveguides as well as reflecting pipes, we were thus left – for better or worse – with optical fibres. This was the thrust of the report which concluded this phase of the project.

Some of the conclusions in the progress report were later presented at an IEE conference in London and published in two papers [7, 8] in the Proceedings of the Conference on "Lasers

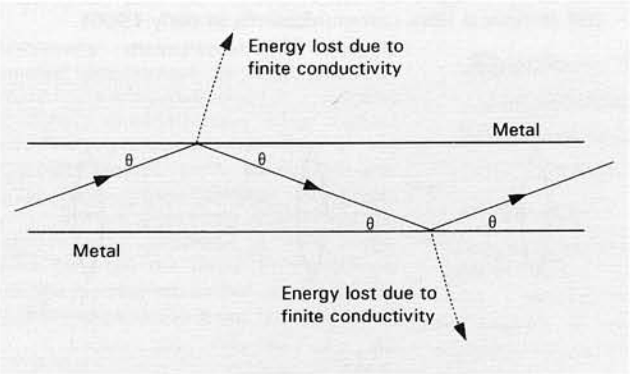

Fig. 2. Waveguide Class 1

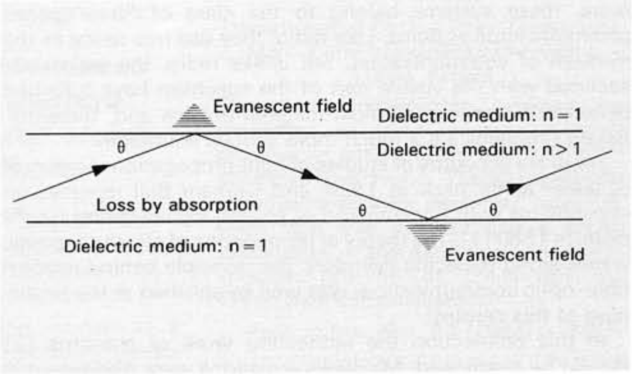

Fig. 3. Waveguide Class 2

and their Applications". The report argued that as the alternatives (reflecting pipe and confocal lens systems) have been rejected, optical fibres and their variants should be investigated. Moreover, in extended discussions, it was stressed that since the suspected cause of high attenuation, in the then available optical fibres, were small quantities of impurities in the virgin glass material, or inhomogeneities in the finished fibre product, a detailed study should be undertaken of the effects of trace impurities and of methods of producing ultra-pure glasses.

One IEE paper [7], when discussing the optical fibre communication medium states: "...a promising type of guide is a cladded glass fibre, provided that certain technological problems can be solved." (Referring to manufacture of high purity glass). Furthermore, it said: "...the system possesses the fundamental advantage in that it can handle a much larger bandwidth – at that time we had in mind single mode fibres, not multimode fibres – in a cable which, at least potentially, need not be more expensive than a copper coaxial cable."

At that time it was noted that the projected costs of a optical fibre cable were dominated by labour costs. This being the case, it was argued, that there are good chances of reducing the cost of the final product through application of engineering methods and automation to production processes. The following comment in reference [7] is of relevance: "As a general conclusion we can state that the choice of a guide for a particular frequency band is largely related to the availability of materials and techniques. It my be well that what appears an impractical approach today may prove to be a success tomorrow, as a result of developments in materials and/or techniques."

In relation to losses in glass fibres the IEE paper [8] had this to say: "With these stipulations in mind we have concluded that of all the guides known to-date, the fibre guide appears to hold most promise, if due to advances in material technology, it becomes possible to manufacture cladded fibres having effective loss tangent about two orders of magnitude better than at present." In fact, in less than ten years down the track this forecast was surpassed.

Elsewhere in the paper was stated: "Fibre guides are attractive in that they are flexible, and are cheap to manufacture. The excessive attenuation may possibly be reduced through research into materials and technology of glassy substances."

The stage was set and the desirable direction of research was identified. But, the success which STL enjoyed in the following years was in no small measure due to the thrust of the convictions of Alex Reeves and his influence on management decisions at that time. At any rate, the researchers believed that the project will be a success: it turned out to be an even bigger success than expected.

5. Optical fibre communications gathers momentum

In 1966 Kao and Hockman [9] supported the earlier predictions with further evidence. Later, in 1968, Kao and Davies [10] published a significant paper, that is largely overlooked in literature. In this paper the authors published results of laboratory measurements on pure quartz and showed conclusively that the effective attenuation in bulk quartz is less than 20 dB/km, thus demonstrating that there are the imperfections in soft glasses that must be responsible for high attenuation in optical fibres.

A few years later Corning produced an optical fibre having attenuation of only 16 dB/km [11]. Thin film guides [12] were studied in 1965, these were the forerunners of integrated optics. Graded index fibres [13] were produced in 1968, and in the early 1970s Corning fabricated the firs fibre in the world having a loss of only 5 dB/km. This quickly improved to 2 dB/km [14].

Beyond this, the work on optical fibre communication systems continued to gather momentum. Indeed, by 1975 there were hardly any industrial nations which did not have a research programme in optical fibre technology, be it for communication or some specialised application. A vast new technology was born: it went beyond optical communications, with applications in a wide variety of fields.

Acknowledgement

This paper is part based on reference [15].

References

1. *A.G. Bell*: Selenium and photophone. The Electrician (1880) pp. 214, 215, 220, 221.
2. *D. Hondros, F. Debye*. Ann. Phys. (Leipzig) **32** (1910) p. 465.
3. *G. Goubau*: Surface waves and their application to transmission lines. J. Appl. Phys., **21** (1950) p. 119.
4. *T.H. Maiman*: Stimulated optical radiation in ruby. Nature, **187** (1960) pp. 493-494.
5. *A. E. Karbowiak*: Trunk Waveguide Communication. Chapman and Hall, 1965.
6. *C.C. Englefield*: Optical pipeline: a tentative assessment. Proc. IEE, **109C** (1962) pp. 26-32.
7. *A.E. Karbowiak*: Communication systems in the visible and infrared spectra: present and future. Proc. Conf. on Lasers and their Applications, IEE London, Sep. 1964, pp. 30/1-30/10.
8. *A.E. Karbowiak*: Guided propagation at optical frequencies. Ibid., pp. 33/1-33/7.
9. *K.C. Kao, G.H. Hockman*: Dielectric fibre surface waveguides for optical frequencies. Proc. IEE, **113** (1966) p. 1151.
10. *K.C. Kao, T.W. Davies*: Spectrophotometric studies of ultra-low-loss optical glasses: single beam method. J. Sci. Instrum., **113** (1968) pp. 1063-1068.
11. *D.B. Keck* et al.: On the ultimate lower limit of attenuation in glass optical waveguides. Appl. Phys. Lett., **22** (1973) pp. 307-309.
12. *A.E. Karbowiak*: A new type of waveguide for light and infrared waves. Electron. Lett., **1** (1965) pp. 47-48.
13. *T. Uchida* et al.: Optical characteristics of light focusing fibre guide and its applications. IEEE J. Quantum Electron., **QE-6** (1970).
14. *P.C. Schultz*: Preparation of very low attenuation optical waveguides. 75th Annual Meeting of American Ceramic Society, Apr. 1974, pp. 1021-1030.
15. *A.E. Karbowiak*: The birth of optical communications. IEE Proc., June 1986, **133**, pp. 202-204.