SAND FROM CENTURIES PAST: SEND FUTURE VOICES FAST*

Nobel Lecture, December 8, 2009

by

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INTRODUCTION

First of all I would like to express my gratitude to the Royal Swedish Academy of Sciences and its Nobel Committee for Physics for awarding me the 2009 Nobel Prize in Physics. It is not often that the award is given for work in applied science. The practical nature of that work, and the time that has since elapsed, means that much has been done over the years, by many people, and the collective result has had a significant impact on society. Therefore this lecture will be about both the research leading up to the key discoveries, and some of the succeeding developments since.

In the 43 years since the publication of my paper with Hockham on glass fiber cables in 1966 [1], the world of telephony has changed vastly. The skepticism of the early years has gradually been subdued by the steady advance of the optical fiber revolution. In the 1970s, while I was working on the pre-production stage research on optical fibers at the ITT Corporation in Roanoke, Virginia, U.S.A., I received two letters: one contained a threatening message accusing me of releasing an evil genie from its bottle; the other, from a farmer in China, asked for a means to allow him to pass a message to his distant wife to bring his lunch. Both letter writers saw a future that has since become history.

THE EARLY DAYS[1]

In 1960, I joined Standard Telecommunications Laboratories Ltd. (STL), a subsidiary of ITT Corporation in the U.K., after having worked as a graduate engineer at Standard Telephones and Cables in Woolwich for some time. Much of the work at STL was devoted to improving the capabilities of the existing communication infrastructure, with a focus on the use of millimeter wave transmission systems.

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1 The following paragraphs are taken essentially verbatim from Ref. [2, 3]

Millimeter waves at 35 to 70 GHz could have a much higher transmission capacity. But the waters were uncharted and the challenges enormous, since radio waves at such frequencies could not be beamed over long distances due to beam divergence and atmospheric absorption. The waves had to be guided by a waveguide. And in the 1950s, research and development work on low-loss circular waveguides in the HE_{11} mode was started. A trial system was deployed in the 1960s. Huge sums were invested, and more were planned, to move this system into the pre-production stage. Public expectations for new telecommunication services such as the video phone had heightened.

I joined the long-haul waveguide group led by Dr. Karbowiak at STL. I was excited to see an actual circular waveguide [4] (Figure 1). I was assigned to look for new methods for microwave and optical transmission. Ray optics and wave theory were used together to gain a better understanding of waveguide problems – then a novel idea. Later, Dr. Karbowiak encouraged me to pursue a doctorate while working at STL. So I registered at University College London and completed the dissertation "Quasi-Optical Waveguides" in two years.

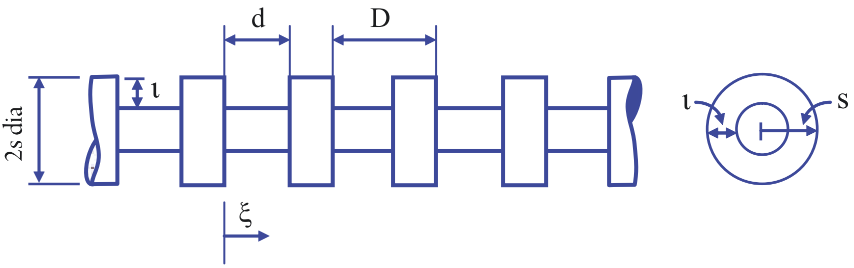

Figure 1. A circular waveguide (after Ref [4]). © [1954] IEEE

The development of the laser in the 1960s gave the telecom community a great dose of optimism that optical communication could be just around the corner. Coherent light was to be the new information carrier with capacity 10^5 times higher than point-to-point microwaves – based on the simple comparison of frequencies: 3×10^{15} Hz (3000 THz) for light versus 3×10^9 Hz (3 GHz) for microwaves.

The race between circular microwave waveguides and optical communication was on, with the odds heavily in favor of the former. In 1960, optical lasers were in their infancy, demonstrated at only a few research laboratories, and performing much below the needed specifications. Optical systems seemed a non-starter. But I still thought the laser had potential. I said to myself: "How can we dismiss the laser so readily? Optical communication is too good to be left on the theoretical shelf." I asked myself two obvious questions:

1. Is the ruby laser a suitable source for optical communication?
2. What material has sufficiently high transparency at such wavelengths?

At that time only two groups in the world were starting to look at the transmission aspect of optical communication, while several other groups were working on solid-state and semiconductor lasers. Lasers emit coherent radiation at optical frequencies, but using such radiation for communication appeared to be very difficult, if not impossible. For optical communication to fulfill its promises, many serious problems remained to be solved.

THE KEY DISCOVERY[2]

In 1963 I was already involved in free-space propagation experiments: The rapid progress of semiconductor and laser technology had opened up a broader scope to explore optical communication realistically. With a HeNe laser beam directed to a spot some distance away, the STL team quickly discovered that the distant laser light flickered. The beam danced around several beam diameters because of atmospheric fluctuations. The team also tried to repeat experiments done by other research laboratories around the world. For example, we set up con-focal lens experiments similar to those at Bell Laboratories: a series of convex lenses were lined up at intervals equal to the focal length. But even in the dead of night when the air was still and even with refocusing every 100 meters, the beam refused to stay within the lens aperture.

Bell Laboratories' experiments using gas lenses were abandoned due to the difficulty of providing satisfactory insulation while maintaining the profiles of the gas lenses. These experiments were struggles in desperation, to control light traveling over long distances.

At STL the thinking shifted towards dielectric waveguides. Dielectric means a non-conductor of electricity; a dielectric waveguide is a waveguide consisting of a dielectric cylinder surrounded by air. Dr. Karbowiak suggested that I and three others should work on his idea of a thin film waveguide [5–6] (Figure 2). But thin film waveguides failed: the confinement was not strong enough and light would escape as it negotiates a bend.

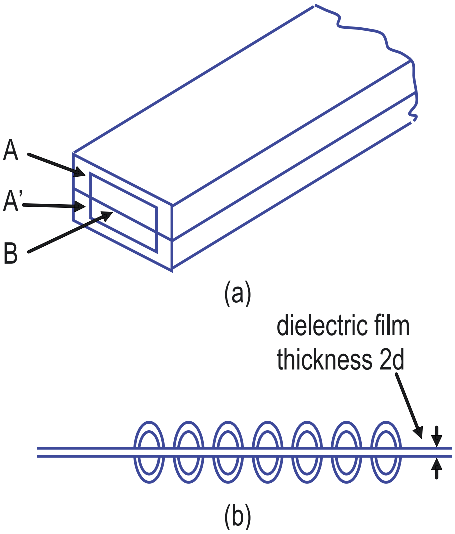

Figure 2. Thin film waveguide (after Ref [6]). © [1965] IEEE

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[2] The following paragraphs are also taken essentially verbatim from Ref. [2, 3]

When Dr. Karbowiak decided to emigrate to Australia, I took over as the project leader and recommended that the team should investigate the loss mechanism of dielectric materials for optical fibers. A small group worked on methods for measuring material loss of low-loss transparent materials. George Hockham joined me to work on the characteristics of dielectric waveguides. With his interest in waveguide theory, he focused on the tolerance requirements for an optical fiber waveguide, in particular, the dimensional tolerance and joint losses. We proceeded to systematically study the physical and waveguide requirements in glass fibers.

In addition, I was also pushing my colleagues in the laser group to work towards a semiconductor laser in the near infrared, with emission characteristics matching the diameter of a single-mode fiber. A single-mode fiber is an optical fiber that is designed for the transmission of a single ray or mode of light as a carrier. The laser had to be made durable and to work at room temperatures without liquid nitrogen cooling. So there were many obstacles. But in the early 1960s, esoteric research was tolerated so long as it was not too costly.

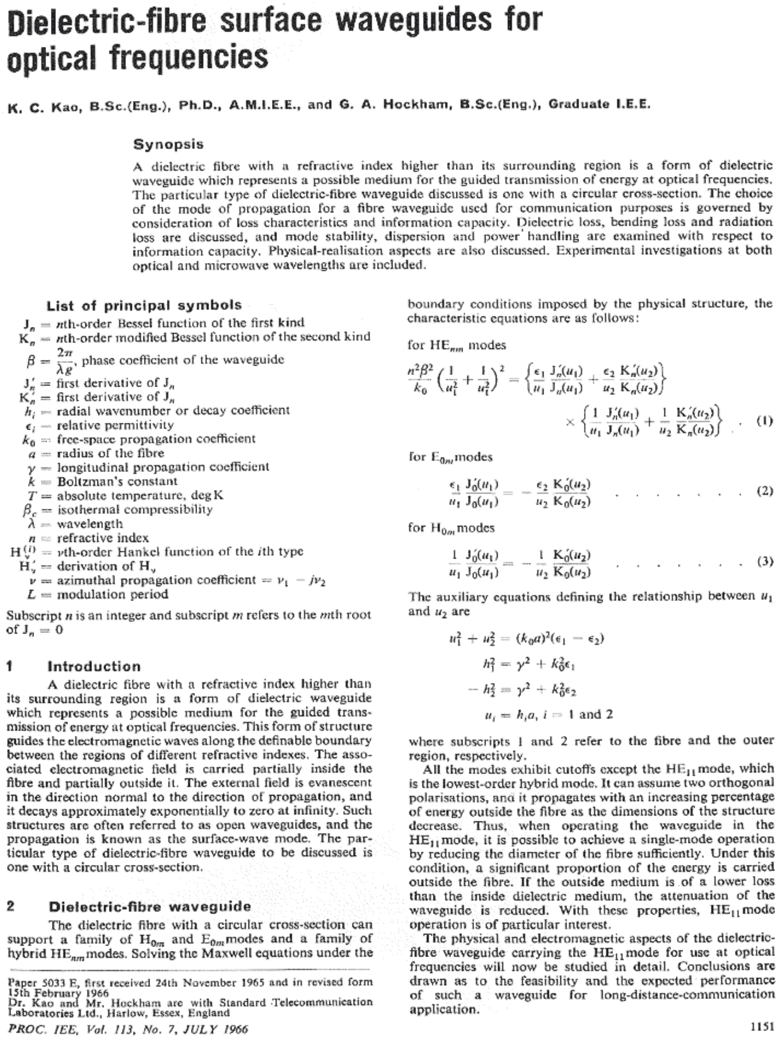
Over the next two years, the team worked towards its goals. We were all novices in the physics and chemistry of materials and in tackling new electromagnetic wave problems. But we made very credible progress in considered steps. We searched the literature, talked to experts, and collected material samples from various glass and polymer companies. We also worked on the theories and developed measurement techniques to carry out a host of experiments. We developed an instrument to measure the spectral loss of very low-loss material, as well as one for scaled simulation experiments to measure fiber loss due to mechanical imperfections.

I zeroed in on glass as a possible transparent material. Glass is made from silica – sand from centuries past – which is plentiful and cheap. The optical loss in transparent materials is due to three mechanisms: (a) intrinsic absorption, (b) extrinsic absorption, and (c) Rayleigh scattering. The intrinsic loss is caused by the infrared absorption of the material structure itself, which determines the wavelength of the transparency regions. The extrinsic loss is due to impurity ions left in the material and the Rayleigh loss is due to the scattering of photons by the structural non-uniformity of the material. For most practical applications such as windows, the transparency of glass was entirely adequate, and no one had studied absorption down to such levels. After talking with many people, I eventually formed the following conclusions.

1. Impurities, particularly transition elements such as Fe, Cu, and Mn, have to be reduced to parts per million (ppm) or even parts per billion (ppb). However, can impurity concentrations be reduced to such low levels?
2. High-temperature glasses are frozen rapidly and should have smaller micro-structures and more even distribution of non-homogeneities than low-temperature glasses such as polymers, and therefore a lower scattering loss.

Our ongoing microwave simulation experiments were also completed. The characteristics of the dielectric waveguide were fully defined in terms of its modes, its dimensional tolerance both for end-to-end mismatch and for its diameter fluctuation along the fiber lengths. Both theory and simulated experiments supported our approach.

Hockham and I wrote a paper entitled "Dielectric-Fibre Surface Waveguides for Optical Frequencies" and submitted it to the *Proceedings of the Institute of Electrical Engineers* (IEE). After the usual review and revision, it appeared in July 1966 – the date now regarded as the birth of optical fiber communication.



Dielectric-fibre surface waveguides for optical frequencies

K. C. Kao, B.Sc.(Eng.), Ph.D., A.M.I.E.E., and G. A. Hockham, B.Sc.(Eng.), Graduate I.E.E.

Synopsis

A dielectric fibre with a refractive index higher than its surrounding region is a form of dielectric waveguide which represents a possible medium for the guided transmission of energy at optical frequencies. The particular type of dielectric-fibre waveguide discussed is one with a circular cross-section. The choice of the mode of propagation for a fibre waveguide used for communication purposes is governed by consideration of loss characteristics and information capacity. Dielectric loss, bending loss and radiation loss are discussed, and mode stability, dispersion and power handling are examined with respect to information capacity. Physical-realisation aspects are also discussed. Experimental investigations at both optical and microwave wavelengths are included.

List of principal symbols

J_n = nth-order Bessel function of the first kind
K_n = nth-order modified Bessel function of the second kind
$\beta = \frac{2\pi}{\lambda g}$, phase coefficient of the waveguide
J_n' = first derivative of J_n
K_n' = first derivative of J_n
h_i = radial wavenumber or decay coefficient
ϵ_i = relative permittivity
k_0 = free-space propagation coefficient
a = radius of the fibre
γ = longitudinal propagation coefficient
k = Boltzman's constant
T = absolute temperature, deg K
β_c = isothermal compressibility
λ = wavelength
n = refractive index
$H_\nu^{(i)}$ = νth-order Hankel function of the ith type
H_ν' = derivation of H_ν
ν = azimuthal propagation coefficient = $\nu_1 - j\nu_2$
L = modulation period

Subscript n is an integer and subscript m refers to the mth root of $J_n = 0$

1 Introduction

A dielectric fibre with a refractive index higher than its surrounding region is a form of dielectric waveguide which represents a possible medium for the guided transmission of energy at optical frequencies. This form of structure guides the electromagnetic waves along the definable boundary between the regions of different refractive indexes. The associated electromagnetic field is carried partially inside the fibre and partially outside it. The external field is evanescent in the direction normal to the direction of propagation, and it decays approximately exponentially to zero at infinity. Such structures are often referred to as open waveguides, and the propagation is known as the surface-wave mode. The particular type of dielectric-fibre waveguide to be discussed is one with a circular cross-section.

2 Dielectric-fibre waveguide

The dielectric fibre with a circular cross-section can support a family of H_{0m} and E_{0m} modes and a family of hybrid HE_{nm} modes. Solving the Maxwell equations under the boundary conditions imposed by the physical structure, the characteristic equations are as follows:

for HE_{nm} modes

$$\frac{n^2\beta^2}{k_0}\left(\frac{1}{u_1^2}+\frac{1}{u_1^2}\right)^2 = \left\{\frac{\epsilon_1}{u_1}\frac{J_n'(u_1)}{J_n(u_1)} + \frac{\epsilon_2}{u_2}\frac{K_n'(u_2)}{K_n(u_2)}\right\} \times \left\{\frac{1}{u_1}\frac{J_n'(u_1)}{J_n(u_1)} + \frac{1}{u_2}\frac{K_n'(u_2)}{K_n(u_2)}\right\} \quad . \quad (1)$$

for E_{0m} modes

$$\frac{\epsilon_1}{u_1}\frac{J_0'(u_1)}{J_0(u_1)} = -\frac{\epsilon_2}{u_2}\frac{K_0'(u_2)}{K_0(u_2)} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (2)$$

for H_{0m} modes

$$\frac{1}{u_1}\frac{J_0'(u_1)}{J_0(u_1)} = -\frac{1}{u_2}\frac{K_0'(u_2)}{K_0(u_2)} \quad . \; . \; . \; . \; . \; . \; . \; . \quad (3)$$

The auxiliary equations defining the relationship between u_1 and u_2 are

$$u_1^2 + u_2^2 = (k_0a)^2(\epsilon_1 - \epsilon_2)$$
$$h_1^2 = \gamma^2 + k_0^2\epsilon_1$$
$$-h_2^2 = \gamma^2 + k_0^2\epsilon_2$$
$$u_i = h_ia, \; i = 1 \text{ and } 2$$

where subscripts 1 and 2 refer to the fibre and the outer region, respectively.

All the modes exhibit cutoffs except the HE_{11} mode, which is the lowest-order hybrid mode. It can assume two orthogonal polarisations, and it propagates with an increasing percentage of energy outside the fibre as the dimensions of the structure decrease. Thus, when operating the waveguide in the HE_{11} mode, it is possible to achieve a single-mode operation by reducing the diameter of the fibre sufficiently. Under this condition, a significant proportion of the energy is carried outside the fibre. If the outside medium is of a lower loss than the inside dielectric medium, the attenuation of the waveguide is reduced. With these properties, HE_{11} mode operation is of particular interest.

The physical and electromagnetic aspects of the dielectric-fibre waveguide carrying the HE_{11} mode for use at optical frequencies will now be studied in detail. Conclusions are drawn as to the feasibility and the expected performance of such a waveguide for long-distance-communication application.

Paper 5033 E, first received 24th November 1965 and in revised form 15th February 1966
Dr. Kao and Mr. Hockham are with Standard Telecommunication Laboratories Ltd., Harlow, Essex, England

PROC. IEE, Vol. 113, No. 7, JULY 1966

Figure 3. The 1966 paper. © [1966] IEEE

THE PAPER

The paper started with a brief discussion of the mode properties in a fiber of circular cross section. It then quickly zeroed in on the material aspects, which were recognized to be the major stumbling block. At the time, the most transparent glass had a loss of 200 dB/km, which would limit transmission to about a few meters – this is very obvious to anyone who has ever peered through a thick piece of glass: nothing can be seen. But our paper pointed out that the intrinsic loss due to scattering could be as low as 1 dB/km, which would have allowed propagation over practical distances. The culprit is the impurities: mainly ferrous and ferric ions at these wavelengths. Quoting from the paper:

> "It is foreseeable that glasses with a bulk loss of about 20 dB/km at around 0.6 micron will be obtained, as the iron-impurity concentration may be reduced to 1 part per million."

In layman terms, if one has a sufficiently "clean" type of glass, one should be able to see through a slab as thick as several hundred meters. That key insight opened up the field of optical communications.

The paper considered many other issues:

- The loss can be reduced if the mode is chosen so that most of the energy is actually outside the fiber.
- The fiber should be surrounded by a cladding of lower index (which later became the standard technology).
- The loss of energy due to bends in the fiber is negligible for bends larger than 1 mm.
- The losses due to non-uniform cross sections were estimated.
- The properties of a single-mode fibre (now the mainstream especially for long-distance and high-speed transmission) were analyzed. It was explained how dispersion limits bandwidth; an example was worked out for a 10 km route – a very bold scenario in 1966.

The paper concluded with the following [1]:

> "The realization of a successful fiber waveguide depends, at present, on the availability of suitable low-loss dielectric material. The crucial material problem appears to be one which is difficult but not impossible to solve. Certainly, the required loss figure of around 20 dB/km is much higher than the lower limit of loss figure imposed by fundamental mechanisms."

Basically all of the predictions pointed accurately to the path of development, and we now have 10^{-2} of the loss and 10^{5} times the bandwidth then forecast – the revolutionary proposal in the 1966 paper was in hindsight too conservative.

The substance of the paper was presented at an IEE meeting on January 27, 1966 [7]. Most of the world did not take notice – except for the British Post Office (BPO) and the U.K. Ministry of Defence, who immediately launched major research programs [8, 9]. By the end of 1966, three groups in the U.K. were studying the various issues involved: I myself at STL; Roberts at BPO; Gambling at Southampton in collaboration with Williams at the Ministry of Defence Laboratory [10].

In the next few years, I traveled the globe to push my idea: to Japan, where enduring friendships were made dating from those early days; to research labs in Germany, in the Netherlands and elsewhere to spread the news. It was obvious to me that until more and more jumped on the bandwagon, the use of glass fibers would not take off. There was widespread skepticism, but I remained steadfast. The global telephony industry is huge, too large to be changed by a single person or even a single country, but I was stubborn and I remained optimistic; slowly others were converted into believers.

The experts at first proclaimed that the materials were the most severe of the intrinsic insurmountable problems. Gambling [9] wrote that British Telecom had been "somewhat scathing" about the proposal earlier, and Bell Laboratories, which could have led the field, took notice only much later. Approaches were made to many glass manufacturers to persuade them to produce the clear glass required. There was eventually a response from Corning, where Bob Maurer led the first group that later produced the glass rods and developed the techniques to make the glass fibers to the required specifications.

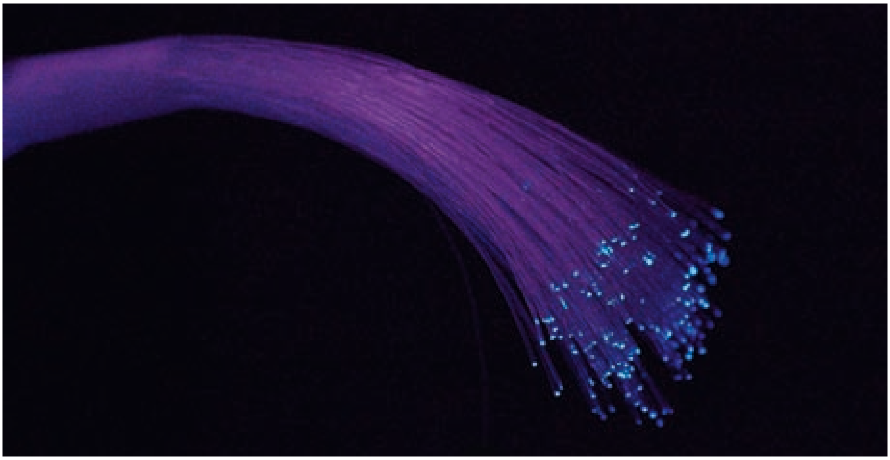


Figure 4. Glass fiber.

Meanwhile, I continued to work on proving the feasibility of glass fibers as the medium for long-haul optical transmission. There were a number of formidable challenges. The first was the measurement techniques for low-loss samples that were obtainable only in lengths of around 20 cm. The problem of assuring surface perfection was also formidable. Another problem is end-surface reflection loss, caused by the polishing process. There was a measurement impasse that demanded the detection of a loss difference between two samples of less than 0.1%, when the total loss of the entire 20 cm sample is only 0.1%. An inexact measurement would have been meaningless.

In 1968 and 1969, I and my colleagues at STL, T. W. Davies, M. W. Jones and C. R. Wright, published a series of papers [11–13] on the attenuation measurements of glass that addressed the above problems. At that time, the measuring instruments called spectrophotometers had a rather limited sensitivity – in the range of 43 dB/km. The measurement was very difficult: even a minute contamination could have caused a loss comparable to the attenuation itself, while surface effects could easily be ten times worse. We assembled a homemade single-beam spectrophotometer that achieved a sensitivity of 21.7 dB/km. Later improvements with a double-beam spectrophotometer yielded a sensitivity down to 4.3 dB/km.

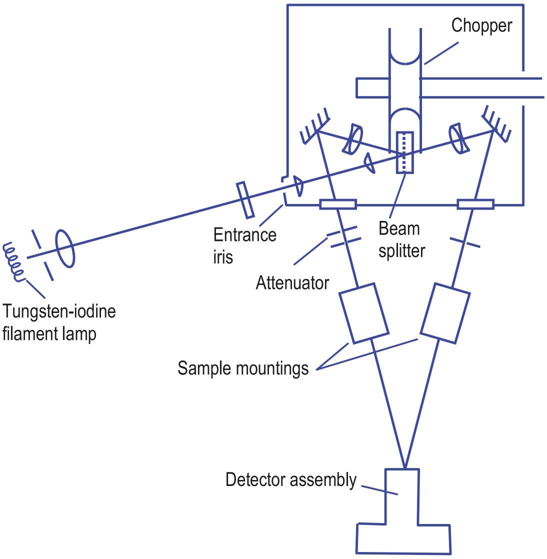


Figure 5. Double-beam spectrophotometer (after Ref [12]).

The reflection effect was measured with a homemade ellipsometer. Measurements were made with fused quartz samples made by plasma deposition, in which the high temperature evaporated the impurity ions. With the sensitive instrument, the attenuation of a number of glass samples was measured and, eureka, the Infrasil sample from Schott Glass showed an attenuation as low as 5 dB/km at a window around 0.85 µm (Figure 6) – at last proving that the removal of impurity would lower the absorption loss to useful levels.

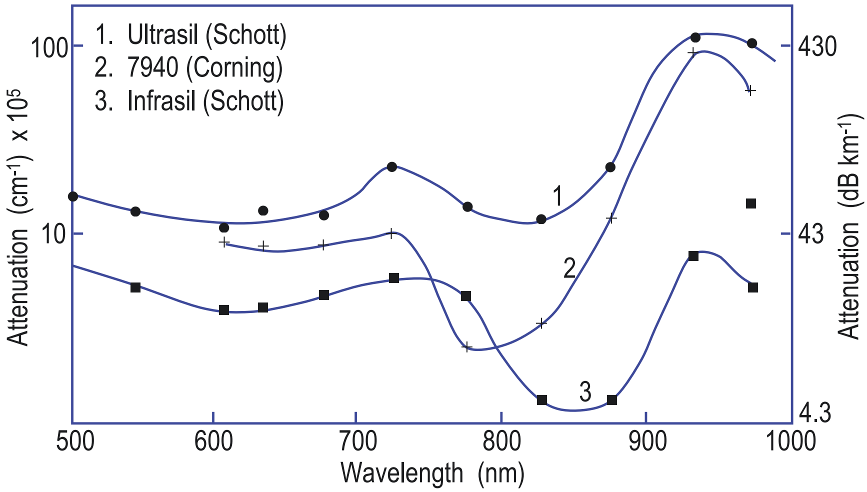


Figure 6. Glass attenuation vs. wavelength (after Ref [12]).

This was really exciting because the low-loss region is right at the GaAs laser emission band. The measurements clearly pointed the way to optical communication – compact GaAs semiconductor lasers as the source, low-cost cladded glass fibers as the transmission medium, and Si or Ge semiconductors for detection [12]. The dream no longer seemed remote. These measurements apparently turned the sentiments of the research community around. The race to develop the first low-loss glass fiber waveguide was on.

In 1967, at Corning, Maurer's chemist colleague P. Schultz helped purify the glass. In 1968, his colleagues D. Keck and F. Zimar helped draw the fibers. By 1970, Corning had produced a fiber waveguide with a loss of 17 dB/km at 0.633 μm using a Ti-diffused core with silica cladding, using the Outside Vapor Deposition (OVD) method [15]. Two years later, they reduced the loss to 4 dB/km for a multimode fiber by replacing the Ti-doped core with a Ge-doped core.

Bell Laboratories finally created a program in optical fiber research in 1969. Their work on hollow light pipes was finally stopped in 1972. Their millimeter wave research program was wound down and eventually abandoned in 1975.

IMPACT ON THE WORLD

Since the deployment of the first-generation, 45 Mb/s fiber optic communication system in 1976, the transmission capacity in a single fiber has rapidly increased: we now talk about terabits per second. In order to understand the fundamental limits of fiber-optic communication, the Terabit per Second Optoelectronic Project was launched [16] during 1982–85, involving ten research organizations. The target technology, three orders of magnitude higher than the then state-of-the-art, was considered impossible at the time.

But the transmission capacity has gradually increased a millionfold from the tens of Mb/s in the early days to many tens of Tb/s in recent years. Data can be carried over millions of km of fibers without going through repeaters, thanks to the invention of the optical fiber amplifier and wavelength division multiplexing. So that is how the industry grew and grew.

The world has been totally transformed because of optical fiber communication. The telephone system has been overhauled and international long distance calls have become easily affordable. Brand new mega-industries in fiber optics including cable manufacturing and equipment, optical devices, network systems and equipment have been created. Hundreds of millions of kilometers of glass fiber cables have been laid, in the ground and in the ocean, creating an intricate web of connectivity that is the foundation of the World Wide Web. The Internet is now more pervasive than the telephone used to be. We browse, we search, we hold net conferences, we blog, we watch videos, we shop, we socialize online. The information revolution that started in the 1990s could not have happened without optical fibers. Over the last few years, fibers have been laid all the way to our homes. All-optical networks that are environmentally green are being contemplated. The revolution in optical fiber communication has not ended – it might still just be at the beginning.

CONCLUSION

The world-wide communication network based on optical fibers has truly shrunk the world and brought human beings closer together. I hardly need to cite technical figures to drive this point home. The news of the Nobel Prize reached me in the middle of the night at 3 am in California, through a telephone call from Stockholm (then in their morning) no doubt carried on optical fibers; congratulations came literally minutes later from friends in Asia (for whom it was evening), again through messages carried on optical fibers. Too much information is not always a good thing: we had to take the phone off the hook that night in order to get some sleep.

In the last twenty years, creative minds have added many ingenious ways to make use of the added bandwidth that has resulted from the use of optical fibers. Optical communication is by now not just a technical advance, but has also caused major changes in society. It will continue to change the way people learn, the way they live and relate to each other, as well as the way they work. For example, manufacturing of all the bits and pieces of a single product can now take place over a dozen locations around the world, providing huge opportunities for people worldwide. The ready accessibility of information has obviously led to more equality and wider participation in public affairs. The evolution continues. Who knows what other forward thinkers will dream of in the future. The unused amount of bandwidth beckons and tempts. Many words, indeed many books have been written about the information society, and I do not wish to add to them here – except to say that it is beyond the dreams of the first serious concept of optical communication in 1966, when even 1 GHz was only a hope.

I would like to thank ITT Corporation, where I developed my career for 30 years, and all those who climbed on to the bandwagon with me in the early days, since without the legions of believers the industry would not have evolved as it did. I planted the seed; Bob Maurer watered it and John MacChesney grew its roots.

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Portrait photo of Professor Kao by photographer Ulla Montan.