

The fiber lightguide

The central component of a lightwave communication system is a fiber no thicker than a human hair, accurately formed of high-purity glass, with low dispersion and losses as low as 1 dB per kilometer.

Alan G. Chynoweth

The realization that the open atmosphere would be a very unreliable medium for the transmission of light led, soon after the invention of the laser, to consideration of the use of conduits, possibly evacuated pipes, for sending the light beams from one place to another, thereby providing a controlled atmosphere. If necessary, such conduits could be fitted with lens and mirror systems to provide beam path correction and beam path redirection. Servomechanisms could be devised to adjust the mirrors and lenses to compensate for such changes as might arise from thermal expansion or other distortions. Such systems could be made to work¹ but undoubtedly they would be very cumbersome and if practical at all, would be so only for very heavy communications traffic routes.

A variation on the conduit approach that was explored in the mid-1960's was to form what is called a gas lens. The scheme was to fill the conduit with gas but to provide a radial temperature gradient by means of a suitable arrangement of heater elements. This radial temperature gradient in turn gave rise to a radial gas-density gradient and hence a radial gradient in the refractive index. Such a radially graded refractive index could provide a waveguiding action for a light beam travelling more or less along the axis of the gas lens. But while experiments established the technical correctness of this approach, it was again likely to be an extremely cumbersome one in practice,² with uncertain reliability.

A way that had been known and practiced for a long time to transmit light over relatively short distances was to use light pipes in which the light is guided principally by internal reflection along internally silvered, hollow tubes or along plastic rods. Such schemes, while useful

in many equipment applications, were not regarded as practical for long-distance communication because of the relatively high attenuations they exhibited. Charles Kao and G. A. Hockman of the Standard Telecommunications Laboratories in England were the first persons to suggest publicly (in 1966) that light pipes or glass fiber guides could be made with sufficiently low loss to be useful as transmission media for relatively long distances.³ At that time some of the best optical glasses had attenuations of the order of several thousand dB/km. What was needed to make a practical communications system was thought (somewhat naively) to be attenuations of 20 dB/km or less. These figures give some indication of the enormous improvement in glass technology that it was realized would be necessary, but Kao felt it might be possible. He was encouraged in his belief by measurements on pure silica that exhibited losses as low as a few tens of dB/km.

The photograph in figure 1 shows a present-day form of a glass fiber used as a medium for light transmission.

Basic types of optical waveguides

From the outset it was recognized in a number of laboratories that the basic guiding structure would be one consisting of a core of a given refractive index surrounded by a cladding layer with a slightly lower refractive index. Such structures could carry propagating optical waveguide modes, the modes being internally reflected or refracted at the core-cladding interface. Extremely pure, low-optical-loss glass would have to be used both for the core and the cladding, but especially for the core as it carries most of the optical energy.

Two basic types of waveguide were considered; these are shown in figure 2. The first is the multimode fiber with a core of relatively large diameter. This fiber has a relatively large numerical aperture, making it suitable for collecting

the light from an incoherent light source such as a light-emitting diode. However the simple multimode fiber has a disadvantage: Because light rays or modes tracing relatively coarse zigzag paths down the guide would take longer to reach the other end of the guide than light travelling along the axis, a multimode guide exhibits more dispersion. Thus, a narrow pulse of light fed in at one end becomes broadened as it travels down the guide. This sets an upper limit on the bandwidth that can be transmitted down a guide of given length.

A way around this difficulty is to make a single-mode fiber, one in which only the modes that travel at very small angles to the axis will propagate. This can be done either by making the core with an extremely small diameter or by making the refractive index difference between the core and the cladding very small. Both approaches set higher demands on the precision of the waveguide-fabrication processes.

What in many ways is a more attractive and more elegant solution to this problem is the graded-index fiber. This is really a solid-state analog to the gas lens mentioned earlier. In this fiber, the refractive index is graded radially, being highest at the axis of the core of the guide and dropping off in some predetermined way towards the circumference of the core. To a first approximation, a parabolic profile for the refractive index is the appropriate one. A mode or ray travelling at a relatively large angle to the axis is swept into a region of progressively lower refractive index. It is bent back by this gradient but for much of the time it is travelling in material with a lower refractive index and therefore has a higher velocity than the ray that travels along the axis in the region of highest refractive index. By choosing the right profile, we can keep these various rays in phase. Thus the multimode fiber with a graded index and sufficiently low optical loss became the prime objective in this search

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Lightwave communications



for an optical-fiber waveguide—a fiber-guide, as it is now called.

Initial uncertainties about glass

From the point of view of the physicist, it is rather sobering to realize how few quantitative answers he could provide to questions asked by the scientists embarking upon the search for a suitable glass technology. Sufficiently detailed, comprehensive information about such basic quantities as the refractive index and the thermal-expansion coefficient of glass as a function of its composition was lacking ten years ago. This made it very much an empirical matter of seeking the optimum combinations for core and cladding materials. It was known, of course, that unprecedented levels of purity had to be achieved in the glass to obtain the required low optical attenuation and it was also known that various transition-metal ions and water were likely to be the most troublesome impurities. But again, the amount of information in the literature on the actual absorption spectra of ions in various glassy hosts was inadequate. Often, it was not known with any great confidence what concentration levels of impurities could be tolerated in the glasses, or even the valence states in which they occurred. Furthermore, there were few analytical approaches available for measuring trace amounts of impurities in the raw materials and the glasses made from them. One of the spin-offs from this glass program has been an increase in the sophistication of related analytical chemical techniques. Neutron activation analysis has proved particularly valuable in analyzing for trace impurities and has enabled the detection of levels down to a few parts per billion.

Another question was, what is the fundamental lower limit to attenuation in a pure glass? Is this due to band-edge tail effects, such as those being postulated for amorphous semiconductors, for example, or to scattering effects from compositional and structural inhomogeneities? As it

turned out, no evidence has been found in these oxide glasses that band-edge tail effects do provide such a limit of practical significance.

By combining absorption spectra obtained on bulk glasses in spectral regions where the absorption is relatively high with spectra obtained on fibers where the optical absorption is extremely low, an absorption spectrum for glass has been achieved⁴ that is probably more complete than for any other material, ranging over

ten orders of magnitude in absorption coefficient, and from 0.05 to 200 microns in wavelength. The absorption spectrum of a soda-lime silicate glass is shown in figure 3. But in all glasses examined, at the edge of the transmission band the actual absorption level could always be attributed to residual impurities. Further purification always resulted in a further lowering of the absorption coefficient.

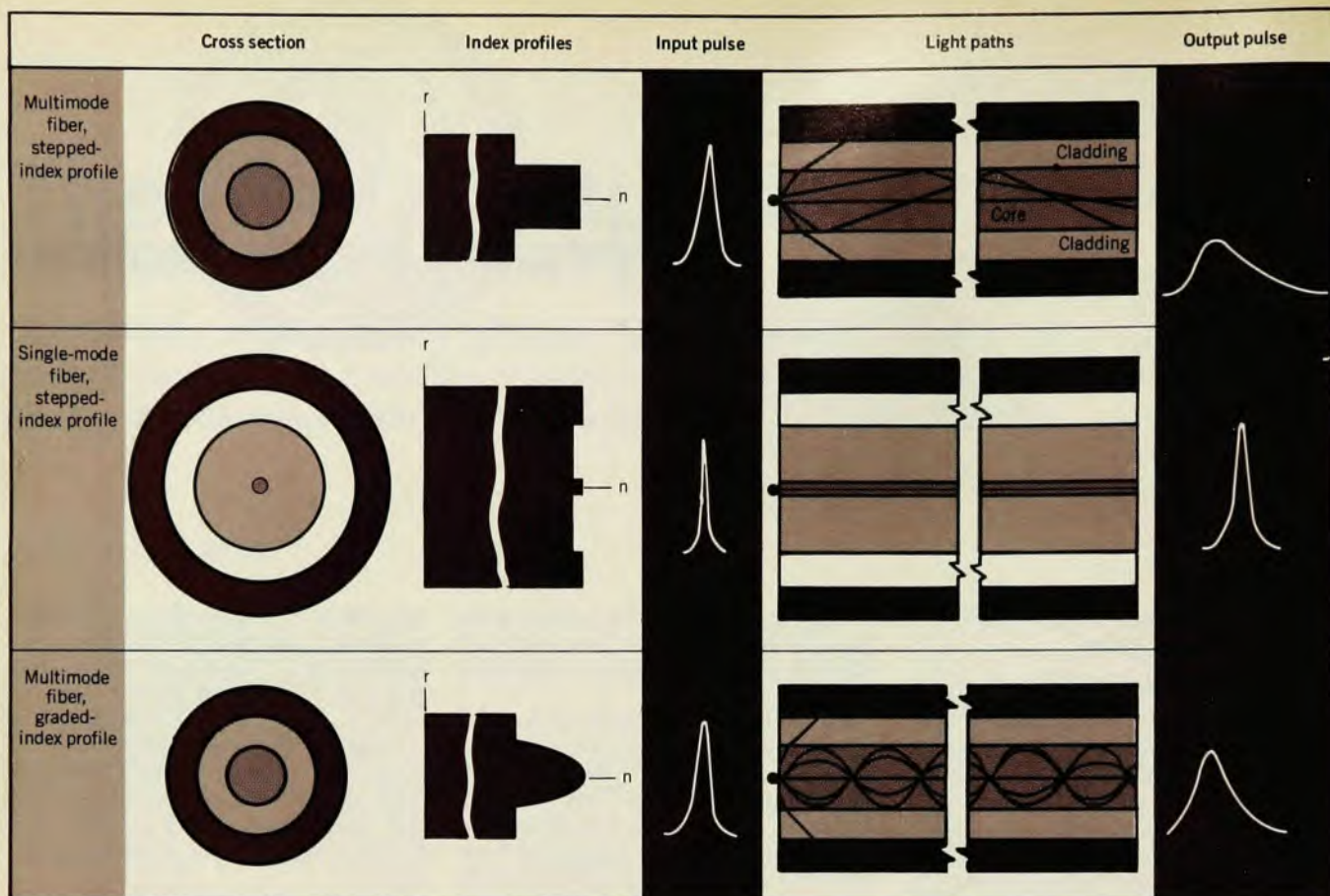
Density and structure fluctuations give

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Conversation piece? Optical waveguides such as this glass fiber may carry your voice, digitally encoded, in the not-too-distant future. The fibers are strong, flexible and can be cabled together; light leakage at gentle bends is not a serious problem.

Figure 1



Schematic representation of the basic types of optical waveguides, showing the cross sections of the glass fibers, their refractive-index

profiles, the paths of typical light rays and the way light pulses spread in traversing the lengths of the fibers. Figure 2

rise to scattering losses—again there was little prior knowledge of what the actual scattering loss levels would be in practical glasses with various compositions. Other sources of light-scattering losses could be anticipated, such as from bubbles, precipitates, cracks, separated phases and irregularities along the core-cladding interface. Then there were other questions that, it was known, would have to be answered eventually, such as: What is the mechanical strength of glass fibers that can be assured over long times and in various types of environment? In the face of all these unknowns, much of the progress had to be empirical.

Choice of glass systems

There are basically two families of glass that can be considered for fabricating optical fibers. There are the multi-component glasses, which contain a number of oxides, and the high-silica glasses, which are basically fused silica, pure or doped. Because they melt at much lower temperatures and because they can be prepared in a wide variety of compositions, the compound glasses proved attractive to various laboratories, principally because of the belief that they offered more versatility and fewer processing problems than the high-temperature silica glasses. Major problems, however, have been the preparation of

sufficiently pure raw materials from which to make the glasses and that of keeping the glass pure during manufacture. High-purity glass manufacture has traditionally been done in platinum crucibles, and contamination from the crucible and the furnace has proved a major problem to many. Nevertheless, impressive progress with multicomponent glasses has been made, particularly by Japanese scientists with the development of their Selfoc glass fibers,⁵ and more recently by scientists at the British Post Office.⁶

The original Selfoc fibers were a particularly interesting early development in the optical-fiber field in that a homogeneous glass rod was converted to the core-cladding configuration by an ion-exchange process performed by placing the glass rod into a molten salt bath. Ion exchange between the rod and the bath gave rise to a graded-composition profile and hence the radially-graded refractive index that produces the self-focussing action of multimode fibers.

More recently the Japanese scientists, like those at the British Post Office, have used a double-crucible technique for forming fibers directly from the melt. Some grading of the index occurs as a result of interdiffusion during the drawing process.⁷

The first really major breakthrough

from an optical-communications viewpoint was made by scientists at Corning Glass Works when they developed fibers based on high silicas. In 1970 they announced⁸ fibers with attenuations as low as 20 dB/km; subsequently they were able to improve this figure to 4 and then 2 dB/km.⁹ They achieved these low-loss fibers by a flame-hydrolysis method in which silicon tetrachloride with, if desired, a suitable dopant halide, would react with oxygen to form a white silica soot deposited on a silica mandrel. Rotating the mandrel and translating the flame back and forth causes a buildup of the white soot deposit. By varying the dopant concentration during this buildup, the Corning scientists were also able to achieve a gradient in the composition. Subsequently the soot is consolidated into a clear glass by an appropriate heat treatment, after which the mandrel is removed. From this "preform," as it is called, a fiber can be drawn, those layers deposited first becoming the core and the later layers the cladding.

Meanwhile it was recognized at Bell Labs also that silica has many attractions to offer: its chemical simplicity and the low losses already known to be achievable, even in commercial types of silica. Ideally it was thought that pure fused silica should be used for the core but the problem was to find a material with a lower

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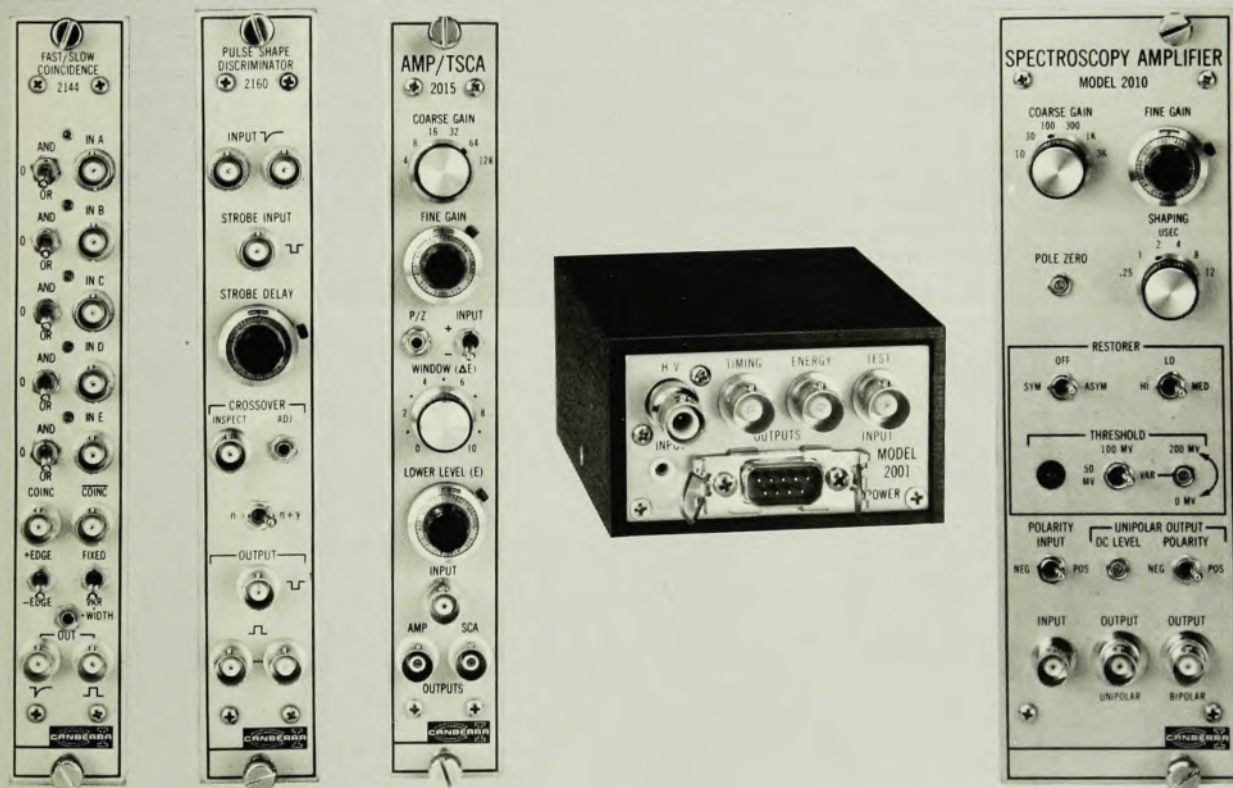
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refractive index that could then be used as cladding. The breakthrough occurred with the discovery that boron-doped silica, namely borosilicate glass, could be prepared with a refractive index lower than that of silica alone.¹⁰ Immediately various configurations exploiting this combination of a silica core and a borosilicate cladding were conceived. It was realized that these could be fabricated by variations of chemical-vapor deposition processes of the sort very familiar to those in semiconductor technology. The basic scheme is to start with an ordinary, commercially available quartz tube and to feed silicon tetrachloride and appropriate doping gases into the tube where they can react, at an appropriate temperature, to deposit a glass layer on the inside of the tube. Again, by varying the gas composition during a run, a radial distribution in the glass composition, and therefore its refractive index, can be achieved.

The usual chemical-vapor deposition process¹¹ in which an oven is placed around the quartz tube is a relatively slow process. A major step forward occurred with the development of a modified chemical-vapor deposition process¹² in which the reaction occurs in the tube where heat is applied by an external oxyhydrogen flame; this process is shown in figure 4. In this way the deposition process has been considerably speeded up and made practical—furthermore, excellent control can be exercised over the radial distribution of the glass composition.

The modified chemical-vapor deposition process has provided a considerable degree of flexibility in the design of waveguide configurations. Silica, the basic material, can be doped with boron



Absorption spectrum of a soda-lime silicate glass, obtained by combining measurements made on bulk glass in the high-attenuation regions with data from fibers in the low-loss regions. (From B. G. Bagley *et al.*, reference 4.)

Figure 3

to *reduce* the refractive index, as mentioned already, or with germania or other compounds to *increase* the refractive index. Thus, if needs be, the inside of the tube may first be coated with borosilicate and then gradually graded towards germania-doped silicate so as to obtain a large numerical aperture. Other variations of this theme can be readily imagined.

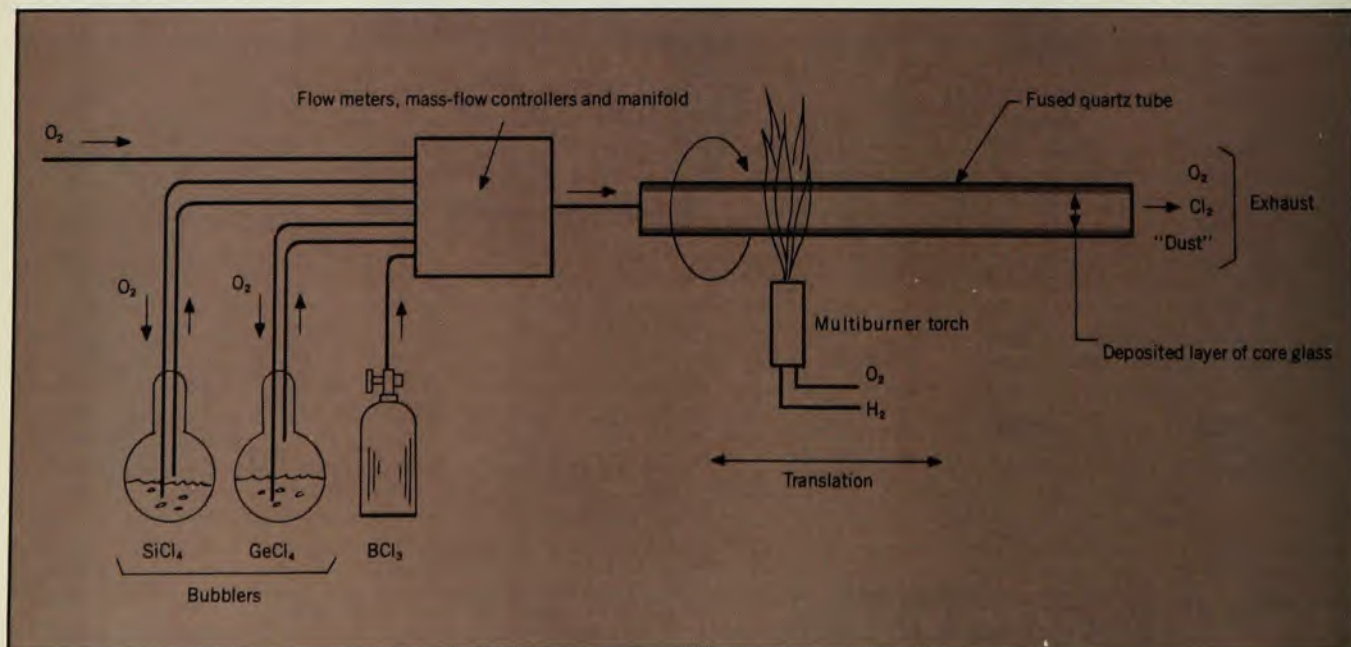
After one of these preforms is prepared

by the modified chemical-vapor deposition method, the reactive gas supply is turned off, the temperature of the flame increased to take the tube up to the softening temperature and the tube is collapsed into a solid rod. In this way the last layers deposited become the core of the waveguide and the first layers deposited, the cladding. The original tube acts as a supporting and protecting element. It turns out that, with care, Nature is very cooperative and allows the collapse of the tube to occur very symmetrically so that the concentric geometry that is necessary for the optical fiber waveguide is retained.

Fiber pulling

After the solid rod preform has been prepared a fiber is pulled from the heated tip of the preform. A fiber several kilometers long can be pulled from most preforms; it is then wound on a drum. With a steadily and smoothly running machine and with suitable control of the various elements, the diameter of the fiber can be kept within very close tolerances. Again Nature has turned out to be surprisingly cooperative—the cross section of the fiber is simply a scaled-down version of the cross section of the very much larger preform. In a typical situation a 1-cm diameter preform is drawn down into a fiber with an outside diameter of about 100 microns.

An alternative approach to fiber pulling that has many attractive control and feedback features is the use of a high-power CO₂ gas laser as the heat source,¹³ as depicted in figure 5. Silica is opaque to the 10.6-micron radiation of the laser, which thus provides a very clean and controllable heat source.



The modified chemical-vapor deposition process for preparing the preforms from which fibers are drawn. In this process, developed by

J. B. MacChesney and P. B. O'Connor, the first layers deposited become the cladding and the last layers, the core.

Figure 4

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One of the little understood properties of glass fibers is that their mechanical strength rapidly deteriorates if they are left unprotected. Pristine fibers, immediately after leaving the drawing head, may have tensile strengths approaching a million pounds per square inch. To preserve this high strength it is necessary to provide a protective coating, usually a polymer of some sort. This is applied, typically, by passing the fiber through a coating cup on its way to the takeup drum.

In addition, a protective plastic jacket, either loosely or tightly fitted, can be placed around the fiber by passing it through an extrusion nozzle through which the molten polymer flows.

Optical characteristics of fibers

A typical absorption curve for a fiber produced by the modified chemical-vapor deposition process is shown in figure 6.¹⁴ It basically represents a background provided by the scattering limit on which is superimposed a small absorption peak due to the OH group. One of the attractions of the processes used for making preforms is that the raw materials are already available in ultrahigh purity for the semiconductor industry, so that other impurity-absorption peaks are usually absent. On the shorter-wavelength side of the OH band, attenuations run typically in the range 3–5 dB/km while on the longer-wavelength side attenuations as low as 1 dB/km at 1.06 microns have been obtained, and they generally fall below 2 dB/km. It is attenuations as low as these, which can now be routinely and reproducibly obtained, that have been the real breakthrough and have aroused the interest of communications-systems engineers in optical communication.

Tight control over the cross-sectional dimensions of the fibers is necessary not only to reduce waveguide losses but also to facilitate cabling and connector techniques. Much progress is being achieved in the stabilization of fiber-pulling techniques; control over the diameter and the core-cladding concentricity to within $\pm 1\%$ is now relatively commonplace.

The importance of being able to control precisely the radial distribution of the refractive index in order to minimize mode dispersion has already been mentioned. To eliminate mode dispersion alone calls for a nearly parabolic distribution of the refractive index. However, in general, material dispersion (akin to chromatic aberration) has to be taken into account as well. Even though the optical wavelength spread in the input pulse is relatively small, over the long distances represented by fibers material-dispersion effects can give rise to significant broadening of the pulse. To minimize these material dispersion effects calls for an optimum profile slightly different from the parabolic. Figure 7 shows a typical profile of this type. (It is worth

noting that for most glasses the material dispersion decreases at longer wavelengths and in fact may become zero between 1.3 and 1.4 microns.)

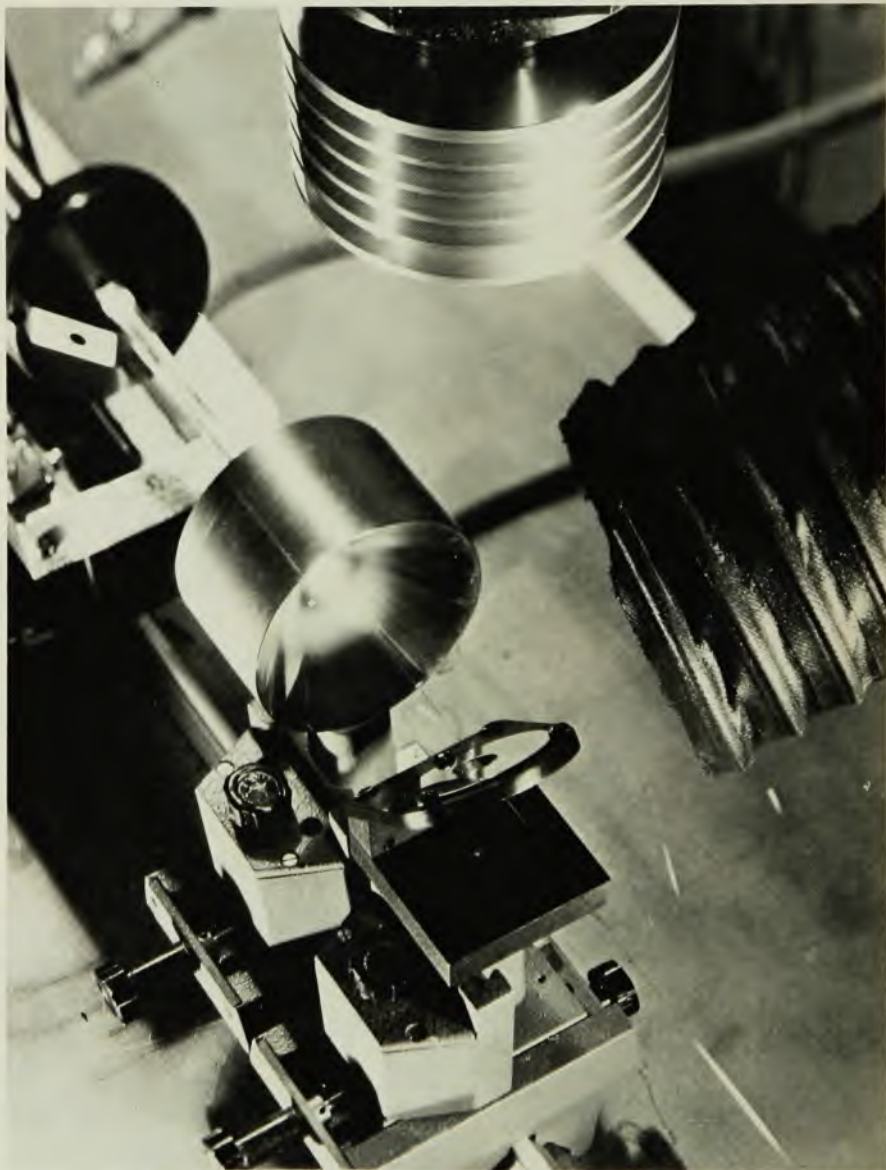
By carefully preparing a series of fibers with slightly different refractive-index profiles, the variation of the pulse dispersion has been measured as a function of the profile in a borosilicate fiber system.¹⁵ Near the optimum profile (for the fiber compositions under study) the pulse broadening is as little as 0.17 nanosec per kilometer. This figure is a factor of about 70 times better than would be achieved by a step-profile fiber with core and cladding refractive indices corresponding to those along the axis of the graded index fiber and the periphery, respectively.

One of the big attractions of optical fiber waveguides—compared, for example, with microwave waveguides—is their flexibility. The flexibility of glass is such that the fibers can be led around equip-

ment and relatively sharp corners quite readily without breaking. However, the tendency of the optical modes to leak further into the cladding at bends introduces additional optical losses. Long constant-radius bends can be lossy but random small changes in curvature, called "microbends," are more serious in practice. These bending losses can be minimized by a judicious choice of the refractive-index difference between core and cladding, and by choosing overall fiber dimensions and supporting coatings that impart a suitable stiffness to the fiber.

Other requirements for optical fibers

From the above discussion, it is correct to draw the conclusion that as far as the optical characteristics of glass fibers are concerned, the desired transmission objectives have been largely met. But there are a number of other requirements that have to be met before fiberguides can be



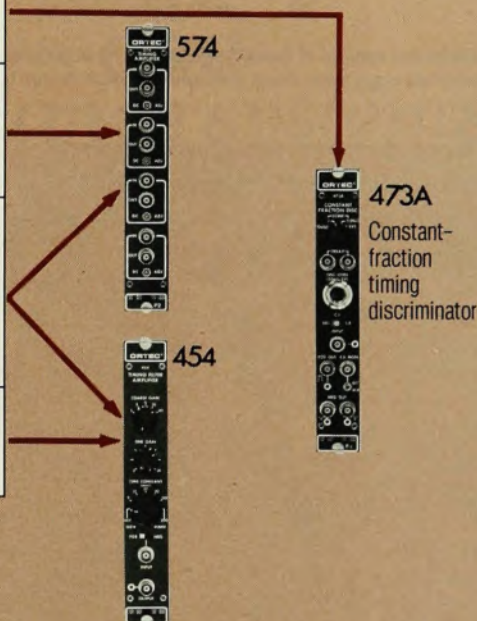
A fiber is being drawn from the tip of a silica-based preform that has been heated by the mirror-focussed beam of a high-power carbon-dioxide laser. (Bell Labs photo.)

Figure 5

What should precede the timing discriminator?

The secret of high-resolution timing, more often than not, is selecting the right amplifier for the occasion.

Detector	Character of timing signal	Processing required
Nal, fast plastic	Fast risetime, good amplitude	None
Fast PMT	Clean shape, low amplitude	Amplify only (integration would degrade timing resolution)
Surface barrier	Low amplitude, occasionally noisy	For low noise, amplify only; otherwise, amplify and filter, fine tuning for best results
Ge(Li)	Noisy, poorly shaped, low amplitude	Amplify and filter, fine tuning for best results



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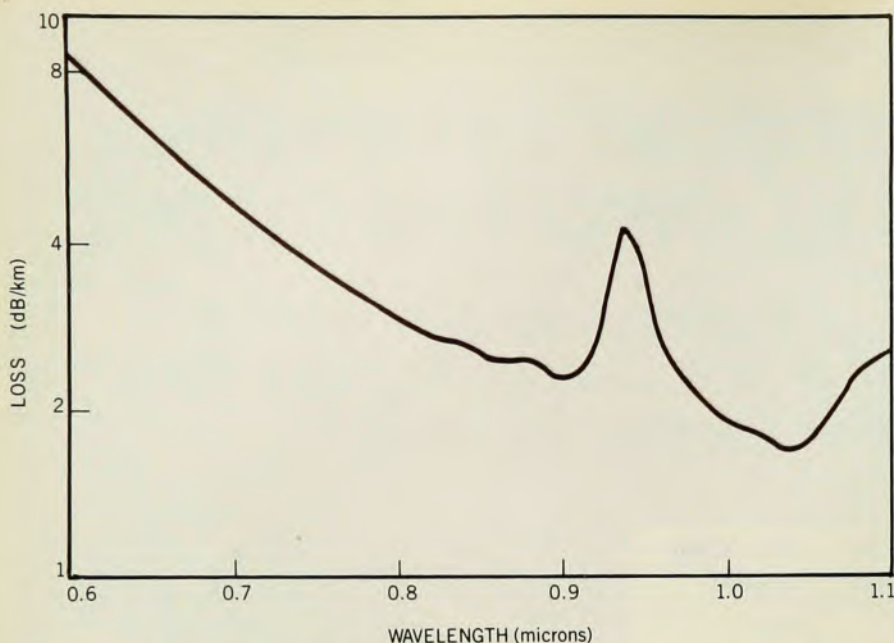
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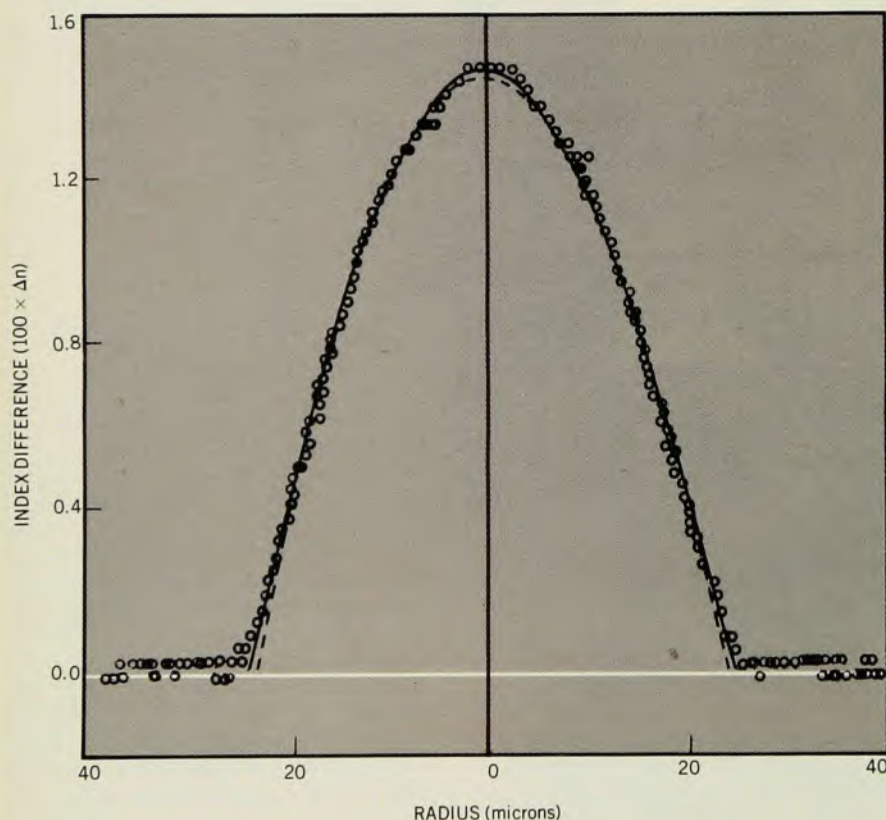
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An absorption spectrum typical of glass fibers drawn from preforms that have been prepared by the modified chemical-vapor deposition process; the peak is due to the OH group. Figure 6



The refractive-index profile of a fiber, measured with an interference-fringe analysis technique. The nearly parabolic radial distribution minimizes mode dispersion. Figure 7

regarded as really *practical* transmission media. Perhaps the most important of these other requirements is that of mechanical strength and stability. If cables made up of numbers of fibers are to be routinely handled and pulled through ducts, for example, they must be able to withstand the large tensile forces to which

they would be subjected in practice.

As mentioned earlier, one of the peculiarities of glass fibers, as yet little understood, is the considerable variation in the tensile strength that is observed from sample to sample. Upper limits to the strength of glass fibers appear to approach a million pounds per square inch,

but in practice many bare samples show strengths only a tenth of this or even much less, down to a hundredth in some cases. The high strengths generally exhibited by freshly made fibers drop off very rapidly with time unless the surface of the fiber is protected in some way. The interplay between microcracks and the surface and chemical attack by water molecules, for example, is very poorly understood at the present time. In the absence of adequate understanding of such stress-corrosion phenomena resort has yet again to be made to the empirical approach; namely, by providing protective coatings to the fibers as soon as possible after drawing. With such methods considerable improvements in the measured strengths of fibers, even after several weeks, have been obtained recently.

Given fibers that meet the desired optical and mechanical characteristics, the next step is to incorporate them into cables made up of a number of fibers. Here again new technologies are being developed. Some of the more important and largely novel features that such cables must possess are designs that:

- ▶ avoid subjecting the individual fibers to intolerable levels of bending;
- ▶ maintain all the individual fibers in some predetermined spatial registry with respect to each other so as to facilitate making splices and connections;
- ▶ result in small overall size so as to retain the basic advantage that optical fibers, each no thicker than a human hair, have over electrical conductor systems, and
- ▶ facilitate splicing sections together, when necessary, in the field.

Progress is being made, however. In some cases, splices with losses averaging about 0.1 dB can be quite routinely produced in development-laboratory facilities. Thus, with fiber optical losses of the order of 4 or 5 dB/km and splice losses of the order of 0.1 dB—bearing in mind that the total loss that can be tolerated between source and receiver for typical optical systems under development can be about 55 dB—it is clear that optical waveguides will be able to run for several kilometers before needing repeaters.

Basic questions

From the foregoing account, it is evident that dramatic progress has been made in the technology of optical waveguides. Within a few years glass technology, responding to the demands made on it by the prospect of optical-communications systems, has lowered the loss exhibited by glass from several thousand dB/km (in typical optical glass) to about 1 dB/km. At the outset of the program these objectives might have appeared almost unobtainable, but one by one the technical problems have been solved.

Much of this progress has been empirical rather than based on rigorous quantitative prediction. This contrasts, for example, with the situation now in semi-

conductor crystals. There the state of sophistication of our knowledge has reached such levels that the chemical compositions and composition structures required for a device to perform a desired function can often be entered into the design from first principles. This is by no means the state of affairs with glass—in many ways the current state of our fundamental knowledge of glass and its properties compares with what we knew of silicon in the early to mid 1950's.

There are very many basic questions that require answers. For example, can glasses with even better optical absorption and scattering properties be discovered? Can ways be found to reduce pulse dispersion further? Can better processes be invented for forming the glasses out of which the fibers are made? Can a higher degree of concentricity and diameter control be achieved in fiber-drawing processes? And what are the practical long-term strengths of optical fibers under various environmental conditions? What are the mechanisms of stress-corrosion cracking of glass? What materials are most suitable for protecting glass from chemical attack? How do such materials adhere to the glass surface? Finally, what are the effects of long-term exposure to low-level ionizing nuclear and cosmic radiation?

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The Model 581 incorporates a high speed, silicon, PIN photodiode, which is thermally controlled to virtually eliminate any changes in detector sensitivity and dark current as a function of temperature. System calibration is highly stable over the long term and measurements are consistently repeatable to within 1%.

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In the Model 581, our technical excellence has worked again to refine a precision instrument that—in lab and in field—will give the stable, repeatable results you can trust EG&G to design. At EG&G, "good enough" just isn't good enough.

For complete specifications, price, and delivery information, contact Neil Bernstein at EG&G Inc., Electro-Optics Division, 35 Congress St., Salem, MA 01970. Or call (617) 745-3200. On the West Coast phone (213) 484-8780.



Our LIGHT MEASURING INSTRUMENTS are never just "good enough."

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