DIRECTIONS IN OPTICAL FIBERS

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Optical-fiber communications has developed into a multibillion dollar industry during the past decade. More than 3 million kilometers of optical fiber are installed annually. AT&T has been a leader in optical communication systems; the company's representative accomplishments include the first full lightwave system trial (in Chicago in 1977) and the first transoceanic optical-fiber systems (in 1989). AT&T is one of the world's largest manufacturers of optical fiber and cable. This article will discuss the relationship between optical-fiber manufacturing and material research and development. Future directions and challenges will be identified.

Background

Optical fibers are hair-thin filaments of glass [silica, 125 μm (micrometers) in diameter] coated with a polymer (62.5 μm thick) to protect the fiber from abrasion. Optical fibers have tensile strengths of almost 1 million pounds per square inch and are capable of sustaining bend diameters as small as 1/16 inch. Pulses of light are typically guided in a 9-μm region of raised refractive index in the center of the glass fiber.

The performance of optical fibers has been of paramount importance throughout the past decade. The two major aspects of performance are optical attenuation and bandwidth. The optical attenuation or loss determines how far pulses of light can travel before their intensity drops to an unacceptably low level for detecting the data signal. The bandwidth, that is, information capacity, of fibers is limited by pulse spreading, which determines the maximum rate at which pulses of light can sent through the fiber. Current commercial systems send as many as 2 billion pulses of light per second, corresponding to approximately 200,000 voice conversations (using speech compression). Experimental optical transmission systems have demonstrated bit rates of 16 Gbits/s.[1] In addition, it is theoretically possible to transmit more than 100 different wavelengths of light simultaneously through a fiber, resulting in theoretical capacities corresponding to 100 million voice conversations.

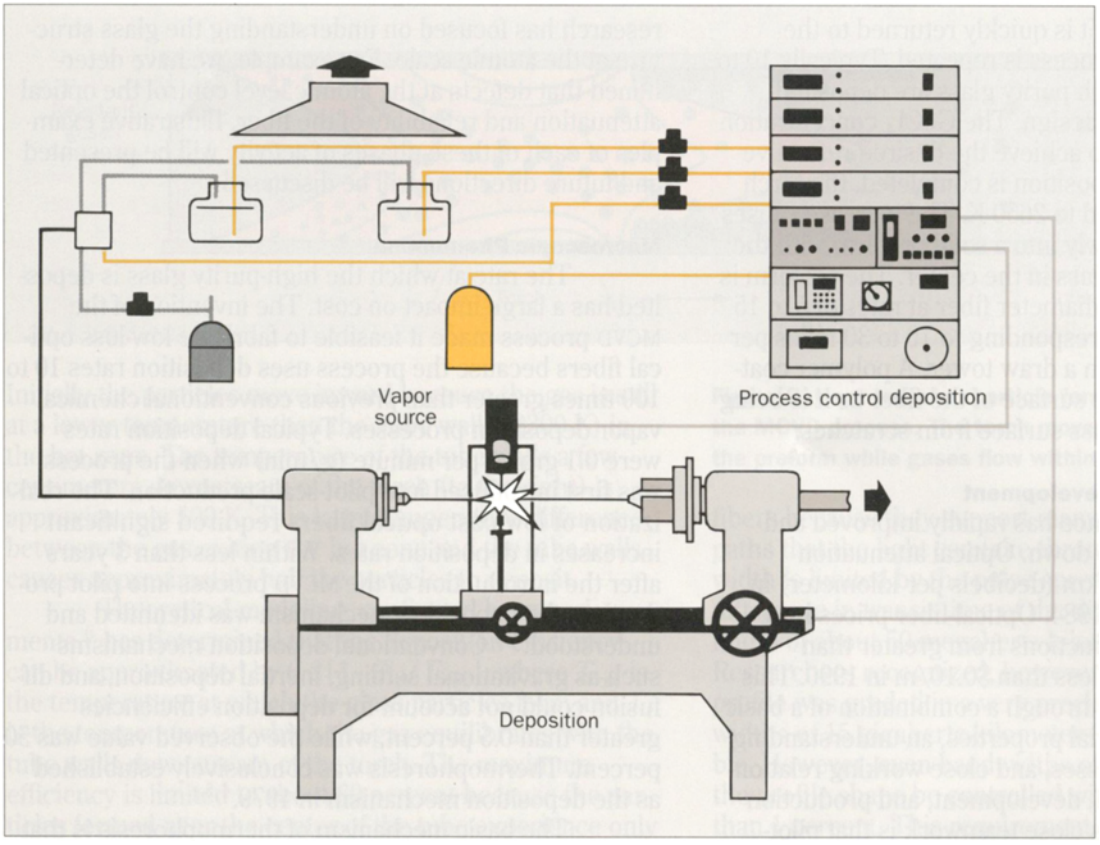

Figure 1. An MCVD preform fabrication station includes the chemical delivery system, glass-working lathe, and process control equipment. During MCVD, the preform rod takes on the cross-section gradient of the final fiber.

Fabrication

Two major steps are involved in fabricating optical fibers. The first step is the fabrication of a glass (mostly silica) rod approximately 2 to 6 cm diameter and 1 m long. The rod is identical to the final fiber except that its diameter is 200 to 500 times larger. This glass rod, called a preform, is then stretched or drawn in a furnace into fiber dimensions and lengths of 25 to 200 km. The most widely used preform fabrication process is the modified chemical vapor deposition (MCVD) process invented at AT&T Bell Laboratories by MacChesney and O'Conner in 1974.[2] A schematic of the process is shown in Figure 1. A silica tube is rotated on a lathe with an oxygen/hydrogen torch traversing the outside. Gaseous reactants, $SiCl_4$, $GeCl_4$, and oxygen, flow through the tube. Addition of Ge to silica raises the refractive index of the core for guiding. The gases heat up and react as they approach the 2300-kelvin (K) hot zone, forming small submicron (less than 0.1 μm) glass particles suspended in the gas. Approximately half the particles deposit on the inside tube walls downstream of the hot zone; the remainder is carried out in the exhaust. The particulate layer is melted to form a solid pore-free glass layer as the hot zone traverses. When the torch reaches the down-

stream end of the tube, it is quickly returned to the entrance end and the process is repeated. Typically 10 to 70 layers of the very high purity glass are deposited, depending on the fiber design. The $GeCl_4$ concentration is varied on each pass to achieve the desired refractive-index profile. When deposition is completed, the torch temperature is increased to 2650 K. The increase causes the tube to collapse slowly into a solid preform with the high-purity deposited glass in the center. The preform is drawn down to 125-μm-diameter fiber at rates of 5 to 15 meters per second (corresponding to 10 to 30 miles per hour) using a furnace on a draw tower. A polymer coating is extruded onto the surface of the fiber as it is being drawn to protect the glass surface from scratches.

Material Science and Development

Fiber performance has rapidly improved and costs have rapidly gone down. Optical attenuation decreased from 20 dB/km (decibels per kilometer) in 1970 to 0.16 dB/km in 1984. Optical-fiber prices have experienced similar reductions from greater than $1.00/meter in 1980 to less than $0.10/m in 1990. This progress was achieved through a combination of a basic understanding of material properties, an understanding of the fabrication processes, and close working relationships between research, development, and production areas. Illustrative of this close teamwork is that pilot-scale production of optical fibers started at the factory in 1975 just 16 months after the MCVD patent was filed.[3]

There has been an evolution in the nature of the material science research during the past 15 years. The emphasis was initially on macroscopic phenomena such as understanding what caused the glass particles to deposit in the MCVD process, the application of polymer coatings on the fiber and the collapse of the tube into a solid preform. The emphasis in the early and mid-1980s shifted to microscopic phenomena. These included the chemistry controlling the incorporation of dopants in the submicron particles and the melting or sintering of these particles into a pore-free glass layer. More recently the research has focused on understanding the glass structure at the atomic scale. For example, we have determined that defects at the atomic level control the optical attenuation and reliability of the fiber. Illustrative examples of each of these phases of activity will be presented and future directions will be discussed.

Macroscopic Phenomena

The rate at which the high-purity glass is deposited has a large impact on cost. The invention of the MCVD process made it feasible to fabricate low-loss optical fibers because the process uses deposition rates 10 to 100 times greater than previous conventional chemical vapor deposition processes. Typical deposition rates were 0.1 grams per minute (g/min) when the process was first introduced into pilot-scale production. The realization of low-cost optical fibers required significant increases in deposition rates. Within less than 3 years after the introduction of the MCVD process into pilot production, the deposition mechanism was identified and understood.[3,4] Conventional deposition mechanisms such as gravitational settling, inertial deposition, and diffusion could not account for deposition efficiencies greater than 0.5 percent, while the observed value was 50 percent. Thermophoresis was conclusively established as the deposition mechanism in 1979.[4,5]

The basic mechanism of thermophoresis is that a small particle suspended in a gas with a temperature gradient experiences a net force and velocity in the direction of decreasing temperature. The net force results from the fact that gas molecules striking the particle on opposite sides have different average velocities because of the temperature gradient.

An understanding of particle deposition in the MCVD process first required a knowledge of the temperature field. Figure 2 illustrates the heat transfer and particle motion in the MCVD process. The reactant gases are heated as they approach the 2300-K hot zone. The chloride reagents ($SiCl_4$ and $GeCl_4$) are oxidized and form small glass particles when the temperature reaches 1600 K.

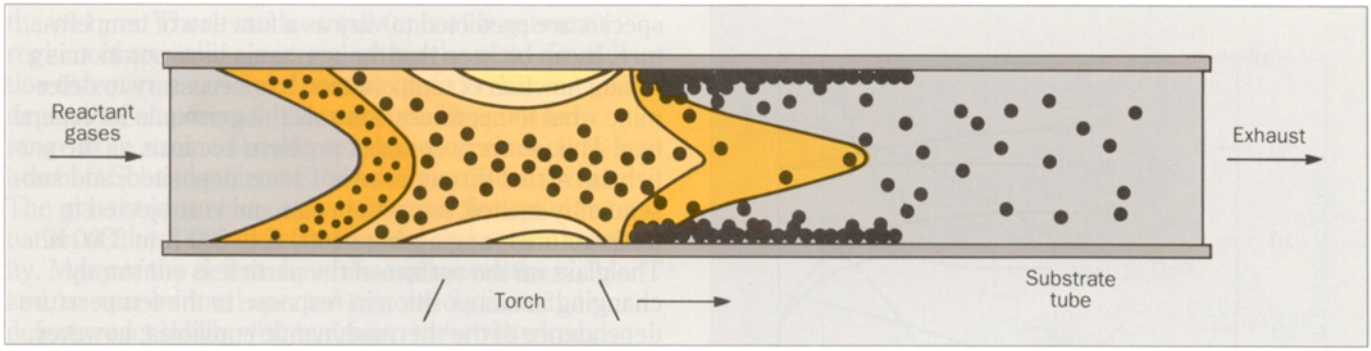

Figure 2. Heat transfer, particle formation, and deposition in the MCVD process. The torch moves along the outside of the preform while gases flow within it.

Initially the particles move inward because the gas is still at a lower temperature than the tube walls (2300 K) in the hot zone. The temperature of the tube walls a few centimeters downstream of the torch (to the right) is approximately 500 K. This large temperature difference between the gas exiting the hot zone and the tube walls causes approximately half the particles to deposit.

Theoretical modeling, confirmed by experiments,[6] has determined that the deposition efficiency can be approximated by $0.8[1 - T_e / T_{rxn}]$, where T_{rxn} is the temperature at which the glass particles form and T_e is the temperature at which the gas equilibrates with the tube walls downstream of the torch. The maximum efficiency is limited to about 60 percent because the particles formed near the center of the tube experience only weak temperature gradients as a result of the radial symmetry. Deposition rates have been increased to over 2 g/min by optimizing the particle deposition with appropriate choices of reagent flow rates, compositions, and hot zone temperature profiles.

Microscopic Phenomena

Optical attenuations of 0.2 dB/km at 1.55 μm had been achieved by 1979, and subsequently much research and development was directed at increasing the bandwidth of fibers. The earliest optical fibers had large cores (50 to 100 μm) with a step-shaped refractive-index profile. These fibers are referred to as step-index multimode fibers because they support many optical modes, that is, paths that the light can take through the fiber. The bandwidth is limited by the pulse spreading caused by the difference in transit time of the different modes to a maximum of about 50 megahertz-kilometers (MHz-km). Researchers recognized, however, that if the refractive profile was graded in a very precise manner, then bandwidths of 15 gigahertz-kilometers (GHz-km) were possible. However, even bandwidths of 1 GHz required that the profile shape be controlled with accuracies better than 1 percent. This requirement motivated work directed at understanding the dopant-incorporation chemistry of the microscopic particles and glass layers.

Germania is the major dopant used for raising the refractive index of the glass. The incorporation efficiency of germania relative to silica varies between 10 and 30 percent depending on deposition conditions. Detailed studies[7,8] of the oxidation of $SiCl_4$ and $GeCl_4$ indicate that the incorporation efficiency of germania is not limited by the oxidation kinetics but is a result of the unfavorable equilibrium at the surface of the particles and deposited glass.[9,10]

$$GeCl_4(g) + O_2(g) \rightleftarrows GeO_2(s) + 2Cl_2(g)$$

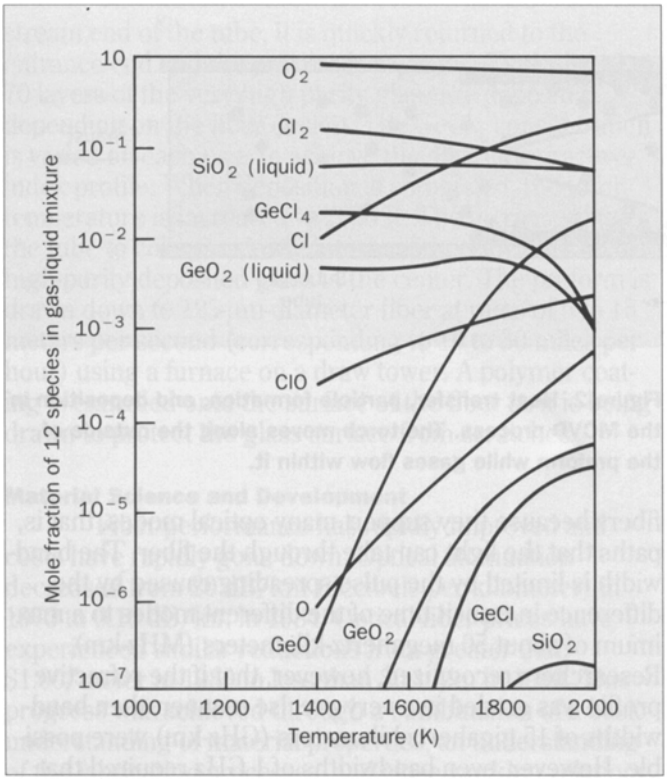

Figure 3. Temperature dependence of chemical species in the MCVD process. The mole fraction of some species is highly dependent on temperature.

The large amounts of chlorine liberated by the oxidation of $SiCl_4$ shift this equilibrium to the left, decreasing the germania incorporation. Additionally, at higher temperatures, the incorporation is also affected by other equilibria such as

$$Cl_2(g) \rightleftarrows 2Cl(g)$$

$$GeO_2(g) \rightleftarrows GeO(g) + \tfrac{1}{2}O_2(g)$$

Figure 3[11] shows how the concentrations of the various species are predicted to vary as a function of temperature. It can be seen that the germania incorporation is a strong function of temperature. It is necessary to determine what temperature controls the germania incorporation. This is a very complex problem because, as the particle is carried through the hot zone, deposited, and subsequently melted, it grows in size and is subjected to temperatures ranging from 1600 K to 500 K to 2300 K. The glass on the surface of the particle is constantly changing in composition in response to the temperature dependence of the thermodynamic equilibria; however, the response of the glass interior to the particle depends on the particle size and the germania diffusivity. The most effective approach to the problem is to use a set of experiments to determine the appropriate temperature controlling the thermodynamics and then use the equilibria to predict the dependence on gas concentrations.

An understanding of the germania chemistry, combined with well-designed chemical delivery systems and process control, permits the routine production of multimode fibers with bandwidths greater than 0.7 GHz-km with values as high as 5 GHz-km.[12,13] Multimode fibers continue to be widely used for local-area networks and data communications. However, for very high speed applications, single-mode fibers with bandwidths greater than 10,000 GHz-km are used. A single-mode fiber has a very small core and small refractive-index difference, which support only one mode or light path through the fiber.

Atomic Phenomena

A major research effort is currently directed at understanding optical-fiber materials at the atomic level. Silica glass consists of a three-dimensional network of silicon and oxygen atoms. Most silica atoms are bonded to 4 oxygen atoms, which in turn are bonded to other silicon atoms. The glass is amorphous—that is, disordered—because the bond angles and bond lengths vary significantly. The Rayleigh scattering loss, which is the predominant contribution to the total loss, is caused by density or compositional fluctuations over dimensions less

than 0.1 μm. There can be small (tens of angstroms) regions of crystalline material within the glass. In addition there are a variety of possible defects that can exist, depending on processing conditions. These defects range from strained bonds, to broken bonds such as broken Si-O-Si bonds, direct Si-Si bonds, or Si-O-O-Si bonds. The glass structure strongly influences the optical attenuation of fibers and their mechanical and optical reliability. Many of the defects have absorptions in the visible and/or near-infrared spectral regions. Some of the defects react slowly with hydrogen to form hydroxyl groups, which have a strong absorption (overtone) at 1.4 μm, which is between the typical operating wavelengths of 1.3 and 1.55 μm.

One defect that has been extensively studied is the Si-O-Si broken bond.[14] It is especially severe in undoped silica fibers drawn at high speeds and temperatures and has an absorption peak at 0.63 μm. This defect will react very rapidly with parts-per-million levels of hydrogen at room temperature forming Si-H and Si-O-H. The absorption at 0.63 μm decreases as the absorption at 1.39 μm (SiOH) and 1.53 μm (SiH) increases. The attenuations at 1.39 and 1.53 μm then slowly decrease, presumably as the Si-H and Si-O-H react to form Si-O-Si plus H_2.

The addition of germania makes the study of defects even more complex. For example, small amounts of germania suppress the formation of the 0.63-μm and 1.53-μm defects for unknown reasons. Germania has a strong tendency to form reduced species, liberating oxygen, at high temperatures. The resultant glass after cooling has large numbers of oxygen-deficient germania defects. These defects will slowly react with hydrogen, resulting in a short-wavelength loss edge that extends to the near-infrared spectrum.

Future Directions and Challenges

Substantial research and development efforts directed at improving the performance of optical fibers has continued over a period of time; however, the targeted areas for improvement have changed. Figure 4

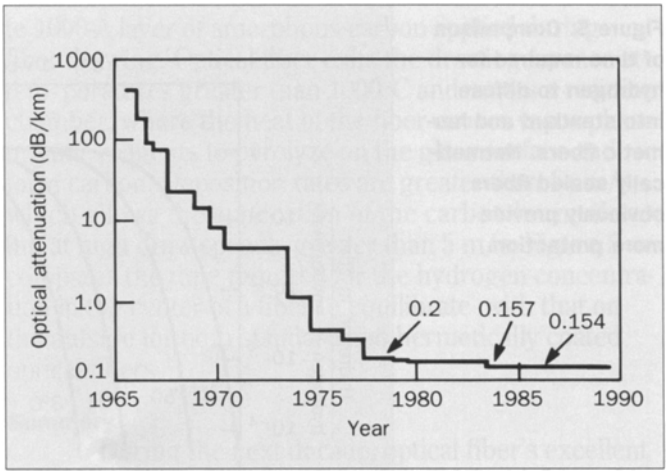

Figure 4. Minimum optical-fiber attenuations as a function of time. Attenuation has clearly improved over the years.

shows how optical attenuations have improved during the last 20 years. It can be seen that the minimum reported attenuations have not improved during the last 4 to 6 years. It is believed that the theoretical minimum attenuation for silica is 0.15 dB/km at 1.57 μm, based on measurements of the Rayleigh scattering losses. Efforts continue to be directed at reducing average losses of production fibers closer to this theoretical limit, generally by reducing the germania concentration in the fibers.

Capacity of optical communication systems continues to double every 18 to 24 months, both for research experiments and commercial systems. Most of the increase is the result of higher-speed lasers and electronics, with the fiber playing a relatively minor role. This is so because current optical communication systems are actually electronic/optic hybrid systems. The fiber is used to transmit optical pulses distances of 35 to 200 km between regenerators. The optical pulses are detected in the regenerators, converted to electrical pulses, processed by high-speed electronics, and then new optical pulses are generated to send through the next section of

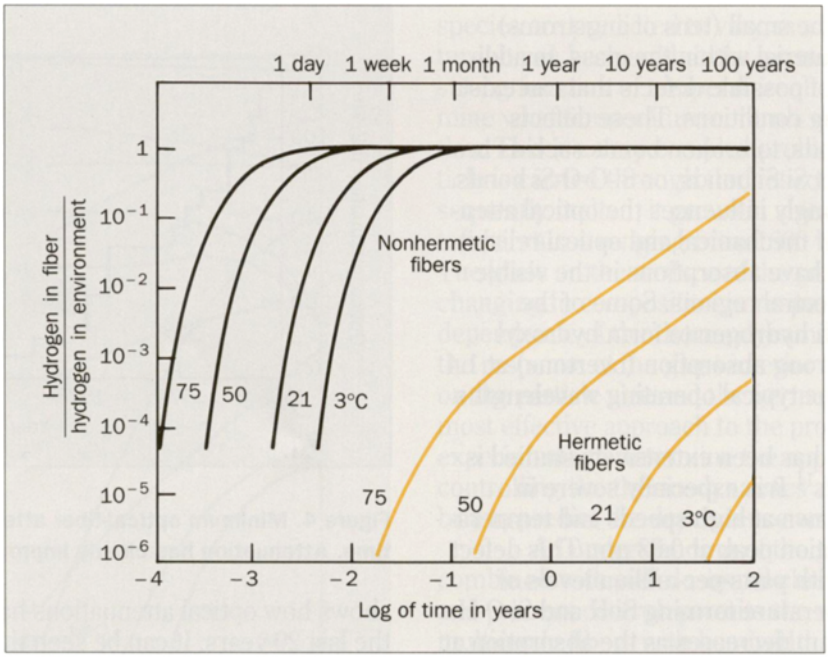

Figure 5. Comparison of time required for hydrogen to diffuse into standard and hermetic fibers. Hermetically sealed fibers obviously provide more protection.

fiber. The regenerators could be electronic bottlenecks, limiting the bit rates and making it impractical to use simultaneously many wavelengths of light in both directions on a fiber. There is a strong desire to develop all-optical regenerators or optical amplifiers that can operate at any bit rate and amplify several different wavelengths of light traveling in either direction. Recent optical-fiber amplifiers have demonstrated these capabilities.

The fiber amplifiers consist of short lengths of single-mode fiber doped with low concentrations of erbium. Dopant atoms are excited to a higher energy level when high-intensity light at 0.98 or 1.48 μm is injected in the fiber. Stimulated emission occurs when the signal light in the 1.55-μm region travels through the fiber, resulting in amplification. Gains greater than 40 dB and output powers of 20 mW have been demonstrated.[15] A recent systems experiment has demonstrated transmission at 3.7 GHz over distances of 9000 km without electronic regenerators.[16] Erbium amplifiers will revolutionize the performance and design of future communication systems. Current materials research is focused on fabricating the desired waveguides and determining the optimum codopants and concentrations.

Another major research challenge is in the area of reliability. Single-mode fibers installed in the ground have almost unlimited potential capacity that can be realized by upgrading electronic and optical components in the terminals as needed. The useful life of many of the fibers will be limited only by their optical and mechanical reliability.

The predominant cause of increased attenuation in optical fibers over periods of years is reaction of hydrogen with defects in the glass. The major sources of hydrogen are the evolution of low levels from organic compounds in the cable and possible high concentrations resulting from corrosion. Hydrogen can diffuse to

the center of a fiber at room temperature in about 14 days. The three major hydrogen species causing increased optical losses are molecular hydrogen, hydroxyl, and germania hydride. The molecular hydrogen losses are reversible, disappearing when the hydrogen diffuses out of the fiber; however, the hydroxyl and germania hydride related losses are permanent. The hydroxyl species has an absorption peak at 1.4 μm. Hydrogen can also react at the reduced germania defects in the glass, forming a species loosely referred to as a germania hydride defect. Germania hydride is believed to be responsible for a short-wavelength loss edge extending to the infrared. This loss due to GeH is generally the major hydrogen-related source of increased attenuation.

Hydrogen-related excess attenuation can be limited either by reducing the number of defects in the glass where hydrogen can react or by minimizing the hydrogen level in the fiber. Reducing the number of defects requires a fundamental understanding of the glass at the atomic scale. Minimizing the hydrogen concentration in a fiber is accomplished by using a well-designed cable structure or by applying a hermetic coating on the surface of the glass to block the diffusion of hydrogen.

The mechanical reliability of fibers is limited by slow weakening of the glass, referred to as *fatigue*, or by degradation of the polymer coating. The fiber becomes fragile if the polymer coating degrades such that it loses its adhesion to the glass and, in the worst case, exposes bare glass, which can easily be damaged by scratches. Fatigue results from the slow growth of flaws or cracks on the surface of the glass because of reaction of water at the flaw tip, which causes bonds to break. Fatigue can be minimized by preventing the surface from being exposed to water, by applying to the glass a hermetic coating or high-performance polymer coating that has good adhesion and prevents pockets or clusters of water from forming at the glass surface, even when the fiber is submerged in water.

The most widely used hermetic coating is a 500- to 1000-Å layer of amorphous carbon applied during fiber drawing. Optical fiber exits the drawing furnace at tem- peratures greater than 1000°C and enters a reaction chamber, where the heat of the fiber causes vapor-phase organic reagents to pyrolyze on the glass surface and form carbon. Deposition rates are greater than 1 μm/s, which allows the application of the carbon hermetic coating at high draw speeds, greater than 5 m/s. Figure 5 compares the time required for the hydrogen concentration in the center of a fiber to equilibrate with that on the outside for both standard and hermetically coated optical fibers.[17]

Summary

During the next decade, optical fiber's excellent optical performance and reliability will be widely used in a variety of applications, including residential telephone and cable television service. Optical communication systems using fiber amplifiers will be in operation with capacities corresponding to more than 1 million simultaneous voice conversations per fiber.

References

1. A. H. Gnack et al., "1 Tbit/skm Transmission Experiment at 166 bit/s Using Conventional Fibre," *Electronics Letters*, Vol. 25, 1987, pp. 1695-1696.
2. J. B. MacChesney and P. B. O'Connor, U.S. patent 4,217,027, 1980.
3. D. L. Myers and F. P. Partus, "Preform Fabrication and Fiber Drawing by Western Electric Product Engineering Control Center," *Bell System Technical Journal*, Vol. 57, No. 6, July-August 1978, p. 1735.
4. P. B. Simpkins, S. Greenberg-Kosinski, and J. B. MacChesney, "Thermophoresis: The mass transfer mechanism in modified chemical vapor deposition," *Journal of Applied Physics*, Vol. 50, No. 9, 1979, pp. 5676-5681.
5. K. L. Walker, G. M. Homsy, and F. T. Geyling, "Thermophoretic deposition of small particles in laminar tube flow," *Journal of Colloid Interface Science*, Vol. 69, No. 1, 1979, pp. 138-147.
6. K. L. Walker, F. T. Geyling, and S. R. Nagel, "Thermophoretic deposition of small particles in the modified chemical vapor deposition (MCVD) process," *Journal of American Ceramic Society*, Vol. 63, No. 9-10, 1980, pp. 552-558.
7. D. L. Wood, J. B. MacChesney, and J. P. Luongo, "Investigations of the Reactions of $SiCl_4$ and O_2 at Elevated Temperatures by Infrared

Spectroscopy," *Journal of Material Science* Vol. 13, 1978, pp. 1761-1768.
8. D. L. Powers, "Kinetics of $SiCl_4$ Oxidation," *Journal of American Ceramic Society*, Vol. 61, 1978, pp. 295-297.
9. P. Kleinert et al., "About the Oxidation of $SiCl_4$ and $GeCl_4$ in Homogeneous Gaseous Phase," *Kristall und Technik*, Vol. 15, No. 9, 1980, pp. 85-90.
10. D. L. Wood et al., "Chemistry of the MCVD Phase for Making Optical Fibers," *Proceedings of Seventh European Conference on Optical Fiber Communication*, Copenhagen, 1978 pp. 1.2-1–1.2-4.
11. K. B. McAfee et al., "Dependence of Equilibria in the Modified Chemical Vapor Deposition Process on $SiCl_4$, $GeCl_4$, and O_2," *Journal of American Ceramic Society*, Vol. 67, 1984, p. 420.
12. D. P. Jablonowski, D. D. Padgette, and J. R. Merten, "Performance of the MCVD preform process in mass production conditions," *Optical Fiber Communications, Technical Digest*, Vol. TUEE2, 1982, pp. 18, 19.
13. A. J. Ritger, F. T. Stone, and F. P. Partus, "Improving the bandwidth of optical fibers made using modified CVD," *Optical Fiber Communications, Technical Digest*, Vol. TUEE4, 1982 pp. 20, 21.
14. P. J. Lemaire and M. D. deCoteau, "Optical Spectra of Silica Core Optical Fibers Exposed to Hydrogen," *Materials Research Society Symposium Proceedings*, Vol. 88, Boston, 1986, pp. 225-232.
15. J. L. Zyskind, C. R. Giles, and E. Desurvire, "Optimal Pump Wavelength for Efficient Er^{3+} Doped Fiber Amplifiers," *Optical Fiber Communications, Technical Digest*, Vol. FA4, 1990, p. 196.
16. L. F. Mollenauer et al., "Experimental Demonstration of Soliton Transmission Over More than 10,000km.," *Conference on Lasers and Electro-Optics/International Quantum Electronics*, Anaheim, California, May 21-25, 1990.
17. P. S. Lemaire et al., "Hydrogen Permeation in Optical Fibers with Hermetic Carbon Coatings," *Electronics Letters*, Vol. 24, 1988, p. 1323.

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