REPORT:

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MAKING SINGLE-MODE PREFORMS BY THE MCVD PROCESS

Introduction

In the last few years, system technology has developed sufficiently to take advantage of the low-loss, high-transmission capability of single-mode fibers. First produced commercially in 1983, single-mode fiber now accounts for over 90 percent of all fiber made at AT&T Network Systems' Atlanta Works. Using the Modified Chemical Vapor Deposition (MCVD) process, glass rods, or preforms, of high-quality doped silica are created from which the fibers are then drawn. These fibers have losses below 0.40 dB/km and 0.22 dB/km at $1.31 \mu m$ and $1.55 \mu m$, respectively, and transmission-rate capabilities in the gigabit-per-second range. Excellent concentricity of both the fiber core and outer diameter allows fibers to be joined into long lengths with a minimal additional loss. These characteristics allow single-mode fibers to be used in systems that operate at high bit rates with regenerator spacings of 30 km to 70 km apart.

Optical fibers for telecommunications consist of a core of high-purity doped silica and a silica cladding. Because the dopants in the core increase the refractive index, lightwaves are totally reflected at the core/cladding interface and guided along the length of the fiber. Since digital systems send out pulses that must be detectable at the receiver, the fiber must not attenuate the pulse too much nor allow the pulse to sprea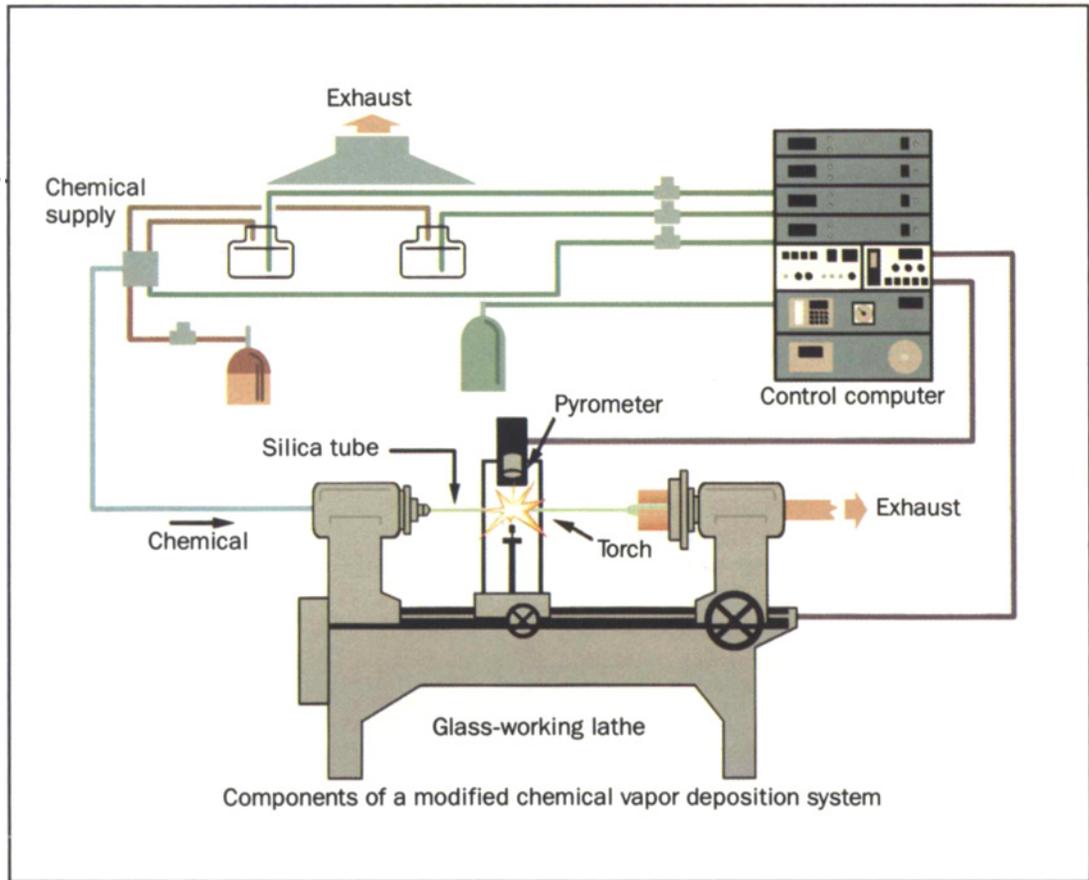d too widely. To achieve this per-formance requires that the core and cladding characteristics be very tightly controlled during the manufacturing process.

The fiber, which has a diameter of 125 μm, is drawn from a preform, and replicates its dimensional and refractive-index characteristics. For example, if the fiber is to have core and outer diameters of $8.0 \mu m$ and $125.0 \mu m$, respectively, then the core and outer diameter of the preform must have the same ratio. The refractive index at corresponding radial positions will also be identical. Since transmission performance is greatly affected by these properties, the ability to produce large quantities of preforms with identical characteristics is essential to the commercial use of fiber for telecommunications.

A process to produce preforms was invented by MacChesney, et al[1] of AT&T Bell Laboratories, Murray Hill, New Jersey, in 1974. Named the Modified Chemical Vapor Deposition (MCVD) process, it uses a fused quartz tube on whose inner surface layers of high-purity glasses are deposited. The tube subsequently becomes the fiber cladding. While research continued at Murray Hill, the development of this process into a viable manufacturing technique occurred from 1975 to 1980 at the AT&T Engineering Research Center and the AT&T Product Engineering Control Center (PECC) in Atlanta, Georgia. Fiber for early trials was produced at the PECC production facilities in Atlanta, and in 1979, work began there on a mass-production facility. Production of multimode fiber cables began in 1980, and has been increasing ever since.[2]

Although multimode systems were very successful, it soon became apparent that the future belonged to single-mode systems.

Figure 1. Components of a modified chemical vapor deposition system.

Exhaust

Chemical supply

Control computer

Pyrometer

Silica tube

Chemical

Torch

Exhaust

Glass-working lathe

Components of a modified chemical vapor deposition system

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Multimode fibers are limited in transmission bandwidth because of the pulse spreading, which results from many modes propagating along the fiber and arriving at the receiver at slightly different times. A single-mode fiber does not have this modal dispersion problem and, therefore, has a bandwidth many times higher. Single-mode preform development was transferred from Murray Hill to Atlanta in 1981. A joint effort between Bell Laboratories and the Product Engineering Control Center was begun. This development effort resulted in a process that was transferred to production in 1983 for the initial system installations. Continued growth in the demand for single-mode fiber cables has resulted in the conversion of over 90 percent of production capacity to single-mode products.

The MCVD Process

A schematic of the MCVD process is shown in Figure 1. There are three main equipment components: a glass-working lathe to hold the tube and torch assembly, a chemical delivery system to provide exact amounts of vapors, and a microprocessor system to monitor and control the process. The rapid growth of the single-mode production capability was made possible by the flexibility of the MCVD process. Although designed to produce multimode preforms, the equipment and process steps were easily converted to single-mode preform production.

The MCVD process begins with the operator mounting the starting tube on the lathe. The tube has an inner diameter of 19 mm, an outer diameter of 25 mm, and is 54

inches in length. The tubes are formed precisely by the suppliers from purified natural quartz. The chemicals to be reacted are delivered to the inside of the tube through a patented rotary chuck mounted to the lathe spindle. An oxyhydrogen torch heats the tube to 1600°C causing the chemical reaction that forms the doped silica. The doped silica is a fine white powder that collects on the inner tube surface downstream of the torch because of the difference in temperature between the gas stream and the tube. As the torch passes

Figure 2. Typical spectral attenuation for production single-mode fiber.
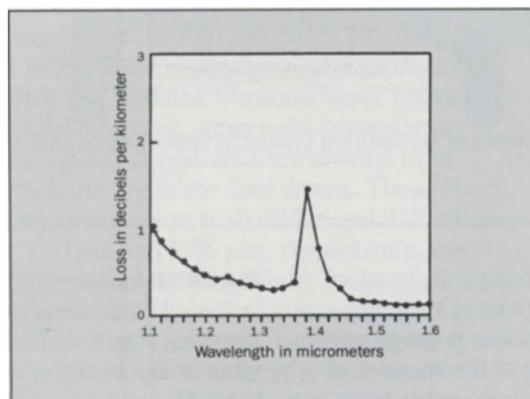
over the accumulated particulate, it is consolidated into a solid glass layer. To make a preform, a predetermined number of layers having the desired composition are deposited. The index of refraction is determined by the amount of dopants, such as germanium or fluorine, contained in each layer. The entire process is automatic with a microprocessor controlling the supply of chemicals and the reaction temperature. The operator normally only monitors the process, but can make manual adjustments if necessary.

After the desired amount of glass has been deposited, it is necessary to close the hole that remains. By heating the tube with the oxyhydrogen torch to within 1900°C to 2000°C, surface-tension effects cause the tube to shrink in diameter. A number of traverses of the torch along the length are required to close the hole completely. A chlorine atmosphere maintained inside the tube inhibits incorporation of the OH radical into the glass, which would result in high loss. One part per million of OH in the deposited glass can cause an absorption loss of 33 dB/km at 1.39 μm. This absorption loss can spread into the 1.30-μm region making the fiber unusable. Typically the loss at 1.39 μm is less the 2.0 dB/km, which corresponds to a hydroxyl content of less than 60 parts per billion.

Early in the development of the single-mode process it became apparent that much higher production rates would be possible compared with those for multimode preforms. To make the step profile of a single-mode fiber shown in Figure 2 requires a number of layers all having the same refractive index. The thickness of these layers is limited only by the capability of the deposition process. In a multimode preform, however, the layer thickness is limited by the necessity of changing the refractive index of each layer slightly in order to obtain the desired parabolic index profile. The bandwidth of the fiber is very dependent on the shape of the profile. In general, the more layers deposited, the higher the resulting bandwidth. By eliminating the need to match a profile, the single-mode-preform process can take advantage of higher deposition rates.

Initial production in 1983 began with a deposition process very similar to that used for
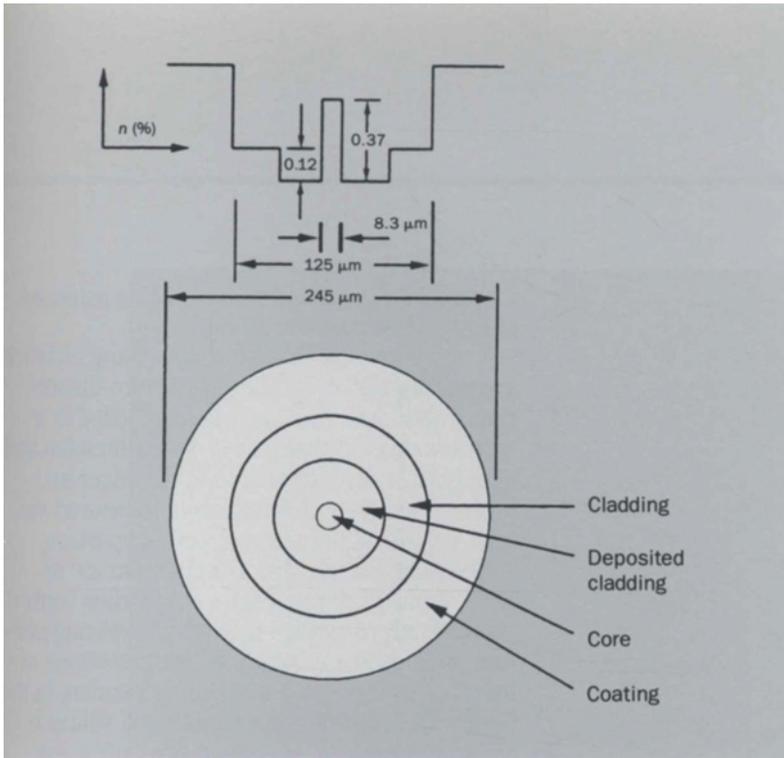
Figure 3. Radial refractive index profile for depressed cladding fiber design.

multimode preforms. Research at Bell Laboratories in Murray Hill demonstrated that a doubling of the amount of clad glass deposited per pass was possible with changes in the deposition conditions. A manufacturing process was subsequently developed and transferred to production in 1984 that increased the deposition rate by 100 percent. Using this process reduced the time to make a preform and improved productivity accordingly. In addition, by varying the speed of the torch along the tube in a special way, a uniform deposition can be achieved over more of the length. This technique has increased productivity also by adding the equivalent of about 1 km of good fiber to each preform. Development is continuing to increase the deposition rate even further.

After their manufacture, preforms are routinely inspected using a laser scanning technique. This inspection gives the dimensions and refractive index characteristics of the preform. The data are used to verify that each
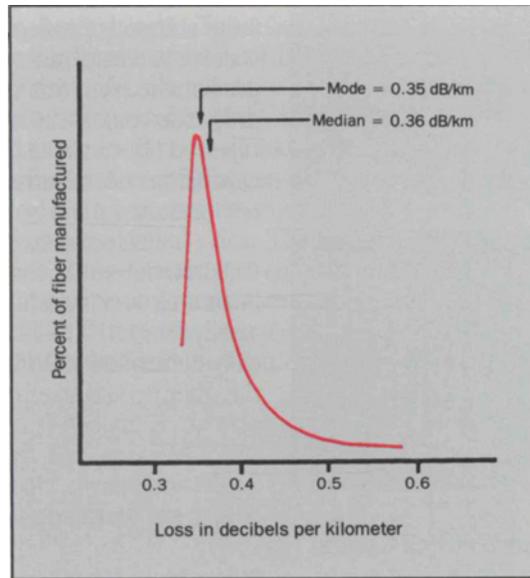
lathe station is producing preforms having the correct values. Transmission properties are predictable from this data and preforms having properties out of the acceptable ranges are rejected. Because of the excellent control capabilities of the lathe station equipment, very few preforms must be scrapped.

Preforms are then drawn into fiber on the draw tower. The tip of the preform is heated to over 2000°C and the fiber is pulled axially from it. The fiber diameter is automatically controlled to 125 ± 2.5 μm. To protect the fiber, a dual layer of ultraviolet-curable acrylate is applied in line with an outer diameter of 245 μm. The fiber is subjected to a 50,000-psi tensile stress before it is spooled to detect any weak spots along the length.

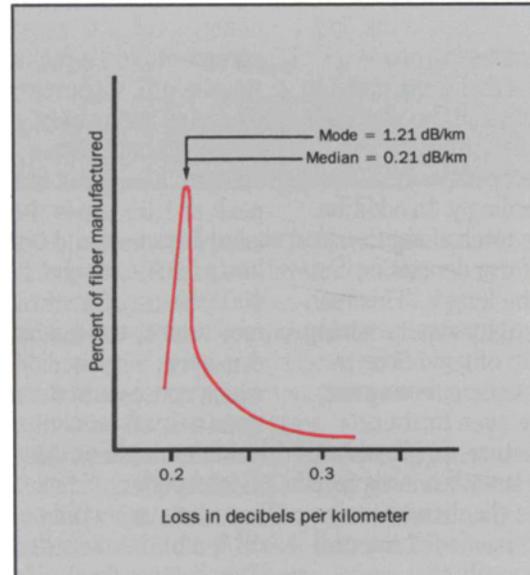### Single-Mode Fiber Performance

The fiber is characterized for its dimensional and transmission properties. Measurements made include loss, cutoff wavelength, dispersion, mode field radius, clad diameter and ovality, coating diameter and concentricity, and core eccentricity. A typical spectral loss result is shown in Figure 3. The peak at 1.39 μm is the hydroxyl absorption loss. Figures 4 and 5 show a distribution of the loss at 1.31 μm and 1.55 μm, respectively, for 400,000 km of fiber made in 1985. Two important values, the median and the mode, are displayed. The median is defined as that value which represents the midpoint of the distribution (i.e., 50 percent of the fiber has loss less than the median). Also shown is the mode or most frequent value. The values for the median and mode are within a few hundredths of a dB/km of the theoretical loss of a perfect fiber. This outstanding performance demonstrates

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Figure 4. Loss distribution for 400,000 km of production single-mode fiber measured at 1.31 μm.

Mode = 0.35 dB/km
Median = 0.36 dB/km

Percent of fiber manufactured

0.3   0.4   0.5   0.6

Loss in decibels per kilometer

Figure 5. Loss distribution for 400,000 km of production single-mode fiber measured at 1.55 μm.

Mode = 1.21 dB/km
Median = 0.21 dB/km

Percent of fiber manufactured

0.2   0.3

Loss in decibels per kilometer

the capability of the process is being achieved in large-scale manufacturing.

The other transmission characteristics are equally well controlled. The zero-dispersion wavelength (λ_0) must be controlled in a narrow range so that pulses do not broaden and thus remain distinguishable at the receiver. Figure 6 shows a distribution of measured values. Very few fibers have a zero-dispersion wavelength outside the acceptable range of 1300 nm to 1320 nm. Mode field radius control is important to ensure cabling and splicing performance. It is a measure of the resistance of the fiber to increased loss due to bending in the cable. The distribution of measured values is shown in Figure 7. Variations are only a few tenths of a micrometer, which again demonstrates the capability of the preform and draw process.

When single-mode systems were proposed, one of the major concerns was whether low-loss splices could be made with an 8-μm core diameter fiber. Splice loss is very dependent on the geometrical relationships of the fibers. Eccentricity is the difference in the position of the center of the core relative to the center of the fiber. If the fiber cores have high eccentricity, splice losses become unacceptable. Production results have demonstrated that the average eccentricity is 0.25 μm. Such low eccentricity makes it possible to achieve mean losses of 0.05 dB for mechanical (bonded) and fusion splices. When combined with the excellent control of the fiber diameter, a mean splice of 0.4 dB is achievable for the 12-fiber array connector originally developed for multimode ribbon cable. This performance has made connectorized single-mode ribbon cable a successful product.
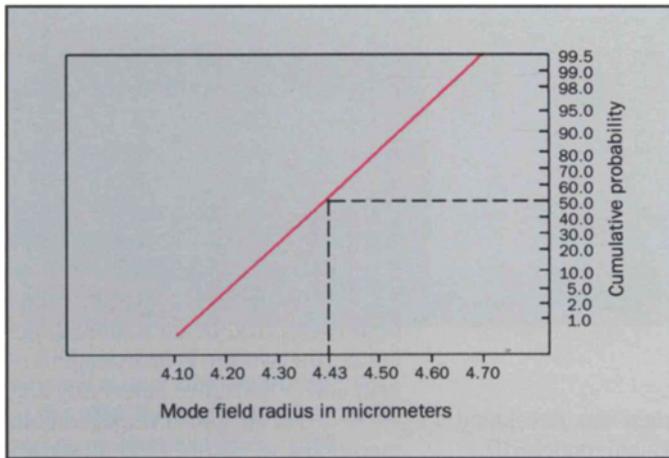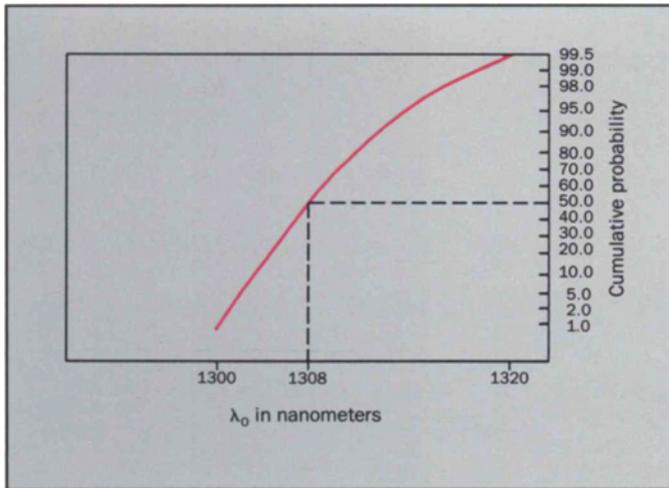
Figure 6. Zero-dispersion wavelength distribution for production single-mode fiber.

Figure 7. Mode field radius distribution for production single-mode fiber.

Future Process Improvements

Single-mode fiber demand continues to grow rapidly, thereby challenging the MCVD process to be more productive and efficient. Development efforts for realizing increased deposition rates and larger preforms are possible methods to achieve the desired productivity. These methods are being actively developed and will be implemented in production over the next few years.

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2. D.P. Jablonowski, "Fiber Manufacturing at AT&T Technologies, Inc." in *Optical Fiber Communications: Fiber Fabrication, Vol. 1,* ed., T. Li, Orlando: Academic Press, 1985, pp. 249-69.

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