# Advances in optical fiber fabrication using vapor phase processing techniques

*By Alan J. Morrow*

Fabrication techniques based on the reaction of vapor phase starting materials to form ultra-pure glasses have proven to be the most effective methods for the production of optical fibers. This is especially true for silica-based glasses and is being investigated for flouride-based glasses. The advantages of vapor phase processing include not only high purity but also flexibility, allowing the fabrication of the complex index profiles required to optimize fiber performance. Advances have been made in all the major processing techniques during the last two years. Progress in fabrication rate and materials has made possible improved fiber designs and enhanced optical properties.

Vapor phase processing for optical fibers is dominated by four techniques: plasma chemical vapor deposition (PCVD), modified chemical vapor deposition (MCVD), vapor phase axial deposition (VAD), and outside vapor phase deposition (OVD). The status of each of these techniques will be reviewed, followed by a more detailed discussion of some recent advances. Knowledge of the basics of the various techniques is assumed.

## *The PCVD process*

In the PCVD process, which is primarily practiced by Philips, advances have been made in rate, size, and water

ALAN J. MORROW is manager of optical fiber and components development at Corning Glass Works in Corning, N.Y. He also serves as cochair of the program committee for the 1988 Conference on Optical Fiber Communication (OFC '88).

***Progress in fabrication rate and materials has made possible improved fiber designs and enhanced optical properties.***

($OH^-$) content. Single-mode (SM) preforms yielding 800 km of fiber have been projected if high quality tubing could be obtained, but 80 km preforms (using rod-in-tube) are the largest reported to date.[1,2] Currently, a 30 km preform size deposited at 1 g/min rate is used in production for SM fiber.[3]

Attenuation of SM fiber made by the PCVD process is slightly higher than for the other processes, with medians of 0.38 and 0.21 dB/km at 1300 and 1550 nm, respectively, currently reported. On the other hand, PCVD clearly leads in multi-mode (MM) bandwidth (BW) with a median of 2.5 GHz · km for 0.20 numerical aperture (NA), 50 μm core fiber.[3]

The maximum deposition rate reported using the PCVD process has increased from less than 0.5 g/min in 1984 to over 3 g/min currently. Optical properties of fibers drawn from preforms fabricated at the higher rates are reported to be equal to that produced at slower rates. Increased taper losses have been largely eliminated by optimizing cavity braking ramps.[2] These high rates require thin walled tubes of high quality. The lack of availability of such tubing is reported to be impeding progress in this area.

High $OH^-$ was once a major problem for the PCVD process for thermodynamic reasons. Recently, however, the addition of flourine to the glass has been shown to effectively reduce the $OH^-$ content. All PCVD fibers now contain F, and $OH^-$ levels as low as ~3 ppb have been demonstrated.[1] Typical production SM fibers range from 3–20 ppb $OH^-$, with the median at about 10 ppb.[3]

Because of its excellent profile control, an attempt is being made to develop a dispersion-flattened SM fiber using the PCVD process. Very tight tubing geometry control is also required to achieve the desired performance. Bending performance was compromised in early designs to optimize the dispersion properties. This obstacle has been partially overcome recently by using a design having a high, thin index ring around the core. The improvement in bending is shown in Fig. 1 where performance approaching standard depressed clad SM is achieved at bend diameters typically required for cabling. Current development efforts are directed toward reducing optical loss, which has tended to be higher for the bend-optimized design.[4]

Plasma-impulse CVD (PICVD) and surface plasma CVD (SPCVD) have also recently been reported and are shown schematically in Fig. 2. In the PCVD process, a moving microwave cavity generates a localized plasma that is scanned along the tube. The PICVD process, developed by Schott, is similar, but instead of a moving plasma, the cavity extends for the full length of the tube. The plasma is pulsed at intervals sufficient to allow the tube to be refilled with fresh reactants, causing almost simultaneous deposition along the length. This eliminates all moving parts and produces excellent profile control with up to 3 GHz · km BW demonstrated. A top rate of 1 g/min and SM losses of 0.6 and 0.3 dB/km at 1300 and 1550 nm have been reported.[5]

In the SPCVD process, developed recently by CNET in France, a surface wave launcher is used to propagate the plasma down the tube. The location of the plasma front, where deposition occurs, is controlled by the input power. Very uniform deposition is reported by controlling the speed of the plasma front. Modulation frequencies as high as 100 Hz can be used. Best results to date are 0.7 g/min and 3.5 dB/km at 850 nm.[6]

## *The MCVD process*

For the MCVD process, practiced by AT&T and others, little has been reported recently with respect to rates and preform sizes. It is likely that most MCVD lathes operate at around 0.5 g/min with higher rate processes largely in development. Up to 2 g/min has been demonstrated for conventional MCVD processing and up to 7 g/min for the RF-plasma enhanced variation of MCVD.[7] Most preforms made in production probably yield about 17 km of fiber, although 40 km rod-in-tube processing may be in some use.

The median attenuation of SM fiber made by the

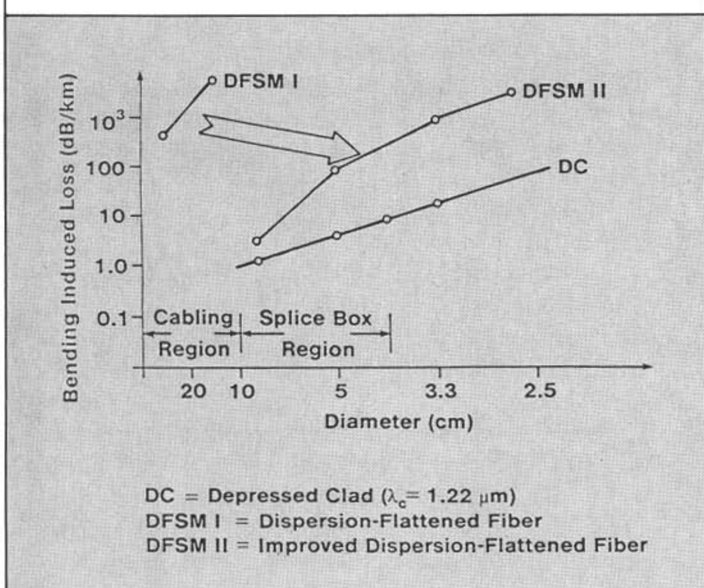



*FIGURE 1. Bending induced losses for various SM designs.*

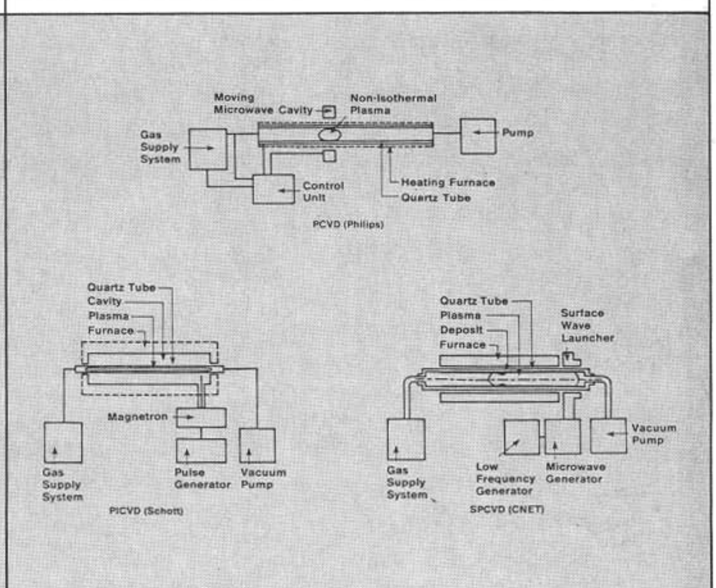



*FIGURE 2. PCVD process variations.*

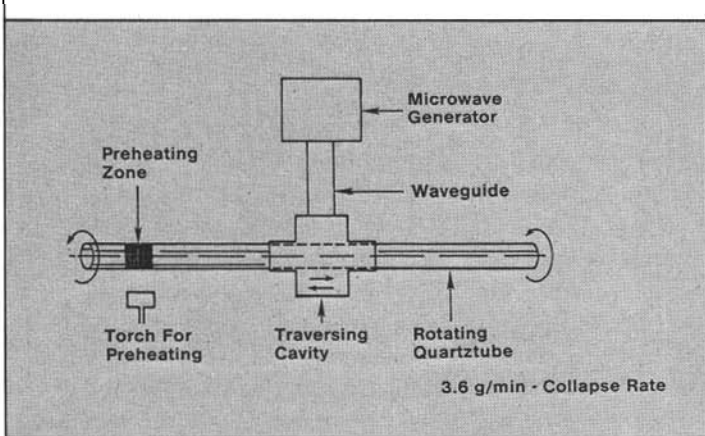



*FIGURE 3. Microwave heating of silica for MCVD process.*

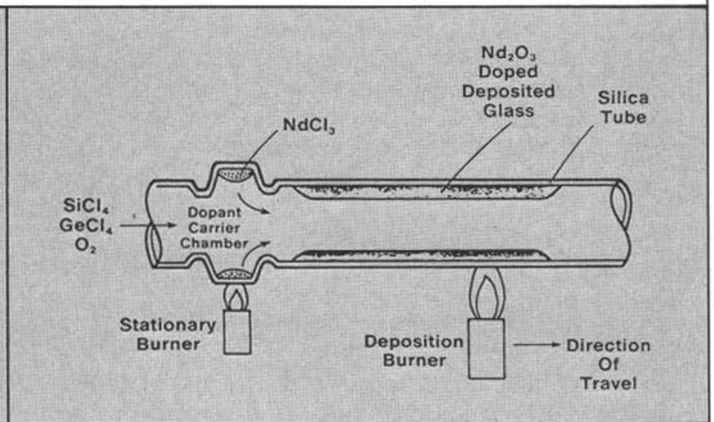



*FIGURE 4. MCVD process for incorporating Nd in low-loss optical fibers.*

MCVD process at AT&T is 0.35 and 0.20 dB/km at 1310 and 1550 nm, respectively.[8] Core eccentricity has been reduced to a median of 0.23 μm, presumably by optimization of tubing geometry and pressure controlled collapse. Work on dispersion-shifted and dispersion-flattened SM fiber is reported in R&D.

A potential MCVD process enhancement (Fig. 3) was reported in 1986 by workers from the Institute of Microwave Technology in Sweden.[9] After heating the silica tube to over 1000°C using a torch, microwave energy is used to heat the tube directly. This effect can be used for deposition, but seems to be most effective in reducing collapse time. The process may be important for collapse of the large OD tubes required for large preforms.

Another MCVD process innovation useful for incorporation of rare earths and other low vapor pressure dopants has been reported by S. Poole, D. Payne, and coworkers at the University of Southampton (Fig. 4).[10] $NdCl_3$, for example, can be dehydrated and melted in a chamber located at the inlet to the preform tube. A stationary burner then vaporizes the $NdCl_3$, which mixes with the $SiCl_4$, $GeCl_4$, and $O_2$. Layers of glass are deposited in the usual manner. Nd, Er, Tb, and Ho have been codoped with Ge to produce SM fibers by this method.

Rare earth doped SM fibers produced by this technique have strong absorption bands, but are of high purity (Fig. 5). The best result to date is <1 dB/km at 1300 nm for SM fiber doped with 150 ppb Nd.[11] SM fibers doped with rare earths fluoresce at wavelengths of interest (Fig. 6). When excited by an Ar laser at 514 nm, for example, useful fiber-based lasers have been demonstrated. Of particular interest are Er-doped fibers, which have been used to make tunable fiber lasers at 1540 nm.[12]

The first report of very high purity $BeF_2$ glass was made last year by Sarhangi and Thompson of Corning using a

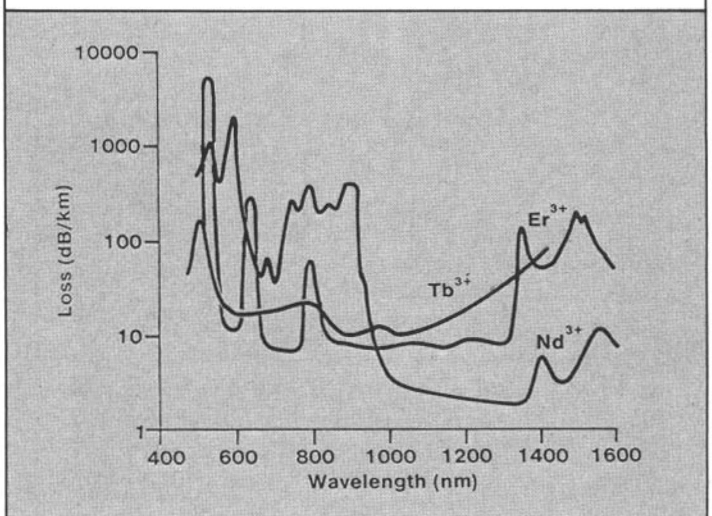



*FIGURE 5. Loss spectra for SM fibers doped with rare earths.*

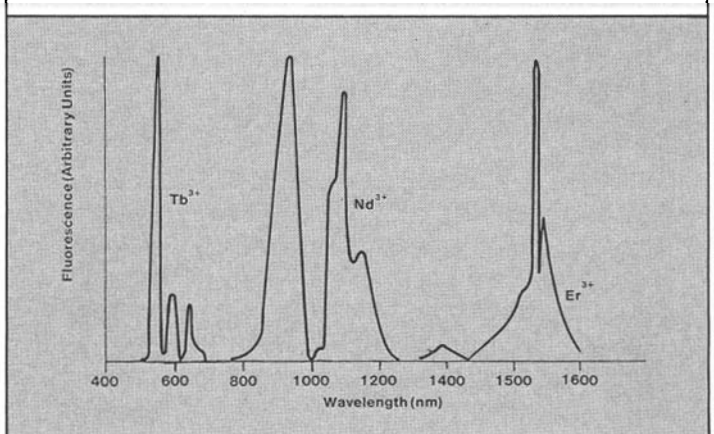
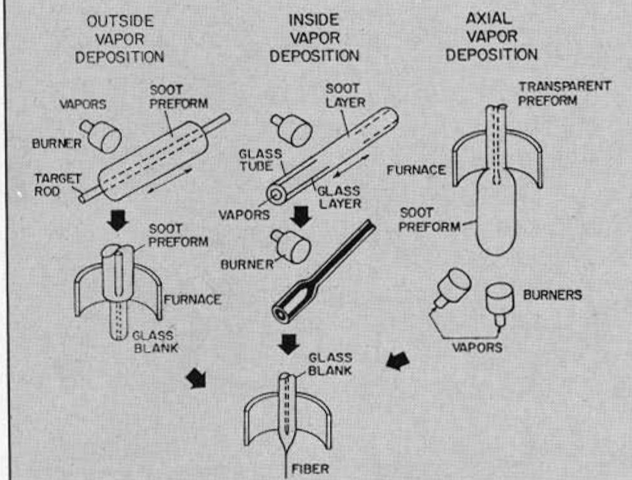



*FIGURE 6. Fluorescence spectra of rare-earth doped fibers.*

# Vapor phase processing techniques




The vapor phase processes used in the fabrication of optical fibers are divided into two types: those for which the glass is deposited on the inside of a tube and those for which the glass is formed in a flame and then collected on the outside of a target. In the outside vapor deposition (OVD) process, layers of fine glass particles (~0.1 μm in diameter) called soot are deposited on a rotating and traversing refractory target. The composition of the reactants is varied to produce the desired profile. When complete, the porous preform is dehydrated and sintered in helium to form a glass blank ready for fiber draw. A variation of OVD is called vapor phase axial deposition (VAD) where the glass is deposited on the end of a rotating and retracting target. In VAD, it is possible to combine the deposition and sintering steps, but this is not practiced commercially. In the inside vapor deposition (IVD) process, also called modified chemical vapor deposition (MCVD), the soot is formed inside a tube by the action of an external flame and deposits downstream from the traversing burner. As the burner continues its travel down the tube, it sinters the soot to solid glass in a layer by layer fashion. After all the layers are deposited, the tube is collapsed to form a solid blank and drawn to fiber. Variants of the IVD process use a plasma generated inside the tube in place of the external flame to enhance deposition rate. (See Fig. 2 of text.)

process similar to MCVD.[13] $BeF_2$ is one of the most stable and simplest fluoride glasses known and, despite its toxicity, is a good candidate for achieving ultra-low loss. The scattering loss of $BeF_2$ glass produced by this technique has been measured to be about ¼ that of $SiO_2$ at 488 nm. This extrapolates to 0.007 dB/km at 2100 nm, where the loss is expected to be minimum for this glass system. Research continues to demonstrate low loss fiber.

## The VAD process

The most important advance in the VAD process in the last two years has been the development of an all synthetic SM process. This has been achieved by two approaches. A one-step process reported by NTT, Sumitomo, and Fujikura produces up to 160 km preforms at up to 10 g/min. A rate of 17 g/min is projected by workers at NTT as more torches are used.[14] A two-step process in production for some months at Furukawa claims 10 g/min for the jacketing step yielding 100 km preforms.[15] A similar process has been reported by Sarkar at Lightwave Technologies Inc. in the United States.[16] These rates were in part achieved through process advances such as multiflame torches and the use of $SiHCl_3$, as well as the use of multiple cladding torches. Median SM fiber loss has improved to 0.35 and 0.21 dB/km at 1300 and 1550 nm using the all-synthetic SM processes. Eccentricity and strength have also improved.[17]

The development of the multi-flame torch has allowed the fabrication of large VAD preforms at higher rates and with improved material efficiency. The mechanism for the improvement in rate using a double flame torch is shown schematically in Fig. 7.[18] Particles formed in a single flame torch typically grow to an average diameter of 0.1 μm. However, because of the longer flame, as well as the option of adding $SiCl_4$ to the outer flame, the average particle diameter in the double flame torch can be three times larger. Large particles are collected more efficiently and at higher density allowing tougher, heavier preforms. A deposition rate of 5.5 g/min and 70% collection efficiency have been reported for $SiO_2$ using a 150 mm diameter target and the double-flame burner design.[19]

The use of $SiHCl_3$ (trichlorosilane) in place of $SiCl_4$ also provides some of the same benefits. $SiHCl_3$'s higher heat of reaction produces a hotter flame resulting in higher density. In addition, this material has a higher vapor pressure than $SiCl_4$ and is low in cost. The rate improvement attainable by substituting $SiHCl_3$ for $SiCl_4$ can be as high as 50% using a double flame torch.[19]

Both of these improvements are used in a schematic representation of the one-step all-synthetic SM process reported by workers at NTT (Fig. 8).[14] The fabrication of

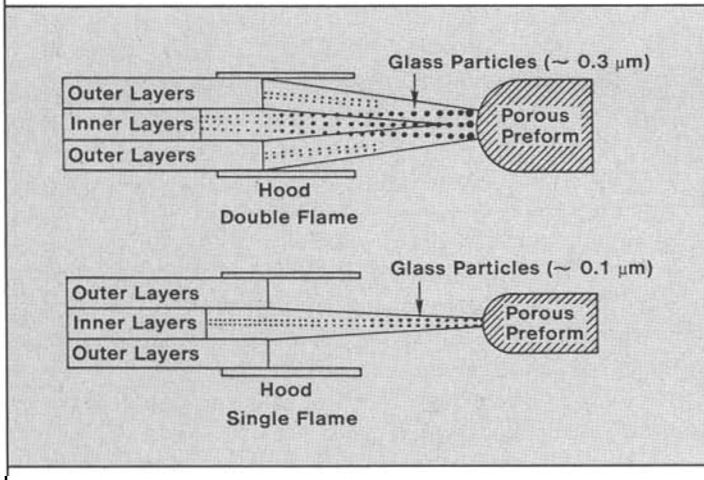



*FIGURE 7. Glass particle growth mechanism in double flame torch.*

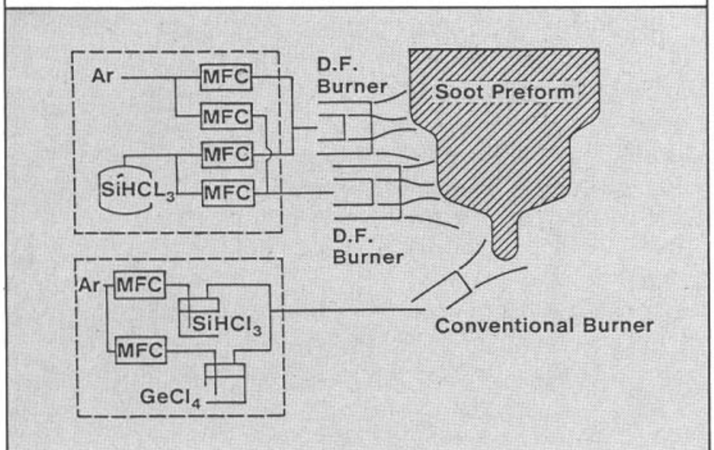



*FIGURE 8. One-step all synthetic SM VAD process.*

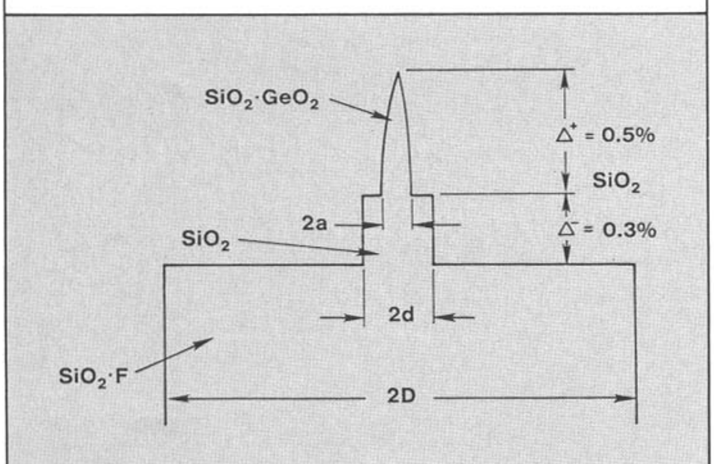



*FIGURE 9. Dispersion-shifted SM fiber design for VAD using F-doped cladding.*

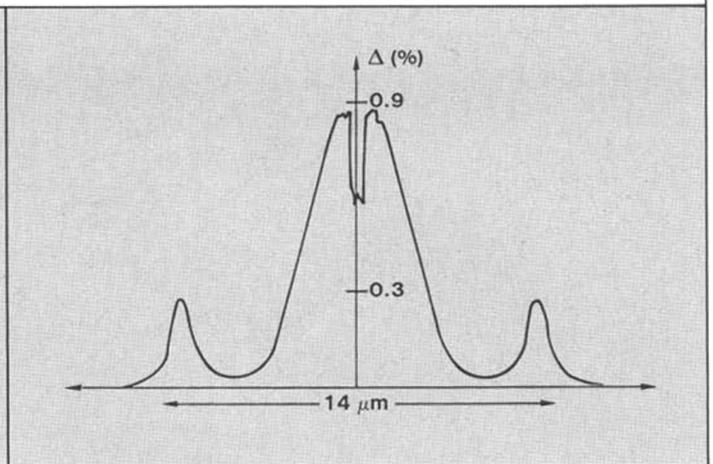



*FIGURE 10. OVD dispersion-shifted SM fiber refractive index profile.*

very large, high density preforms make it possible to produce the required 16:1 clad-to-core ratio in one laydown step. $SiHCl_3$ is reportedly used in both core and cladding, and the $SiHCl_3$ in the cladding torches is directly vaporized without use of a carrier gas.

A variation of the VAD process in which F is doped in the cladding glass during sintering has been used to produce low loss pure silica core SM fiber. The fiber is reported to be less sensitive to the effects of hydrogen and radiation than $GeO_2-SiO_2$ core SM fibers made by VAD.[20] An extension of the silica core process has also been used to produce dispersion-shifted SM fibers.[21] The design, shown schematically in Fig. 9, allows reduced $GeO_2$ in the core and reportedly produces reduced bending sensitivity compared to simple step designs. The minimum loss reported is 0.20 dB/km at 1550 nm.

## The OVD process

For the OVD process practiced primarily by Corning Glass Works, recent advances in deposition rate and preform size have been reported. SM preforms yielding 90 km of fiber are currently being produced at an average rate of 9 g/min in production.[22] Rates in excess of 10 g/min and preforms yielding more than 160 km of fiber have been made in development. Fiber drawn from these large preforms is characterized by a high degree of optical and physical uniformity. The median loss of OVD-produced SM fiber continues to be 0.35 and 0.20 dB/km at 1300 and 1550 nm, respectively. The median BW for 0.20 NA, 50 μm core MM fiber is 1.6 GHz · km. OVD fibers are made completely from synthetic silica and, as a result, exhibit excellent fiber geometry control and high strength.[23]

The first commercially available dispersion-shifted SM fiber was produced using the OVD process. A segmented core design (Fig. 10) is used which has advantages for zero dispersion control, as well as bending performance.[24] It is particularly well suited for the OVD process which excels in radial profile control of $GeO_2$-$SiO_2$ glasses. Fiber produced using this design has a median loss of 0.22 dB/km and a minimum loss of 0.17 dB/km at 1550 nm. Bending sensitivity at 1550 nm is comparable to that of standard SM fiber at 1300 nm. Further improvements in bending performance are possible by increasing the cut-off wavelength beyond 1300 nm.[25]

An exceptionally high NA MM fiber has also been reported using the OVD process.[26] The NA of 0.40 was achieved though the use of $GeO_2$ doping in the core and $B_2O_3$ and F doping in the cladding. This type of fiber is effectively fabricated by the OVD process because the cladding composition can be optimized to minimize stress. The composition profile shown in Fig. 11 produces a well-controlled index profile (Fig. 12), where the approximately 4% total index difference between core and cladding is achieved by +3% due to $GeO_2$ and −1% due to $B_2O_3$ and F. Despite the presence of a small amount of $B_2O_3$ in the outer core and cladding, attenuations in the 1–2 dB/km range at 1300 nm were measured. Fibers of this type may be useful as graded index lenses or for severe bending applications.

Relatively high vapor pressure organometallic source compounds for use in the OVD process have also been reported. These have been used to dope OVD fibers with

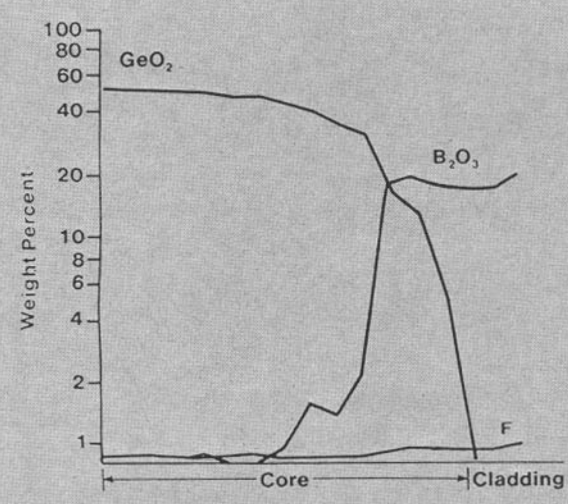
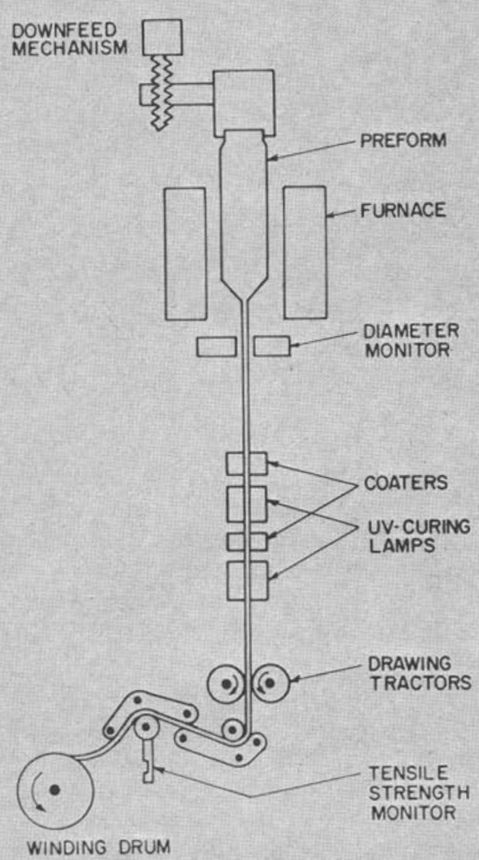



*FIGURE 11. Composition profile for 0.40 NA fiber.*

## *Optical fiber draw*




The final step in optical fiber fabrication is the draw process as shown schematically here. A number of heat sources have been used to achieve the 2000–2200°C temperature required. The most commonly used furnace designs use inductively heated zirconia and resistively heated graphite. The blank is fed into the furnace at a constant rate. After dropping a gob of glass, the fiber is threaded through a tractor and a feedback loop established between the measured diameter of the fiber and the pulling rate.

Typically, two layers of coating are applied: one for cushioning against microbending and the other for ease of handling. The coatings are either thermally cured or cured using ultra-violet lights. Silicones or acrylates are most commonly used. Finally, the fiber is proof-tested for strength and wrapped on a spool for optical measurement.

*Future advances in vapor phase processing techniques for optical fibers will probably focus on two objectives: reduction of overall cost and special applications.*

rare earth oxides.[27] $GeO_2$-$SiO_2$ MM fibers doped with $CeO_2$ exhibited a loss increase at short wavelengths but relatively low loss at 1300 nm as shown in Fig. 13. Nd and Eu doped glasses have also been made by OVD.

Future advances in vapor phase processing techniques for optical fibers will probably focus on two objectives: reduction of overall cost and special applications. Higher rates, larger blanks, and possibly lower cost dopants will be needed to bring fiber-to-the-home at a reasonable cost. Work will also continue on special fibers such as those optimized for use in very long or very dense links; on fibers for sensors and other devices, and on attributes useful for military applications, such as resistance to radiation. Finally, work on fluoride glasses made using vapor phase processing holds promise for the next major breakthrough in optical loss.

## Acknowledgments

The assistance of the following individuals and organizations is gratefully acknowledged: Donald Jablonowski of AT&T Network Systems, R. Th. Kersten of Schott Glaswerke, Hans Lydtin and Hartwig Schaper of Philips, Hiroshi Murata and Katsuhiko Okubo of Furukawa, and David Payne and Simon Poole of the University of Southampton.

### REFERENCES

1. H. Lydtin, "PCVD: A technique suitable for large-scale fabrication of optical fibers," J. Lightwave Tech. **LT-4,** 1034–1038 (1986).
2. P. Geittner, H.J. Hagemann, J. Warnier, and H. Wilson, "PCVD at high deposition rates," J. Lightwave Tech. **LT-4,** 818–822 (1986).
3. H. Schaper, Private Communication (1987).
4. P.K. Bachmann, P. Geittner, D. Leers, and H. Wilson, "Loss reduction in fluorine-doped SM- and high NA-PCVD fibers," J. Lightwave Tech. **LT-4,** 813–817 (1986)
5. H. Bauch, V. Paquet, and W. Siefert, "Preparation of optical fiber preforms by plasma-impulse-CVD," SPIE, **584,** 33–37 (1985).
6. D. Pavy, M. Moisan, S. Saada, P. Chollet, P. Leprince, and J. Marec, "Fabrication of optical fiber preforms by a new surface-plasma CVD process," ECOC, **1,** 19–22 (1986).
7. K.L. Walker, "Status of the modified chemical vapor deposition process," *Digest of Conference on Optical Fiber Communication* (Optical Society of America, Washington, D.C., 1986), paper WA3.
8. D. Jablonowski, Private Communications.
9. Y. Hassler, G. Boling, and S. Peckel, "Homogeneous heating technique in preform manufacturing," *Digest of Conference on Optical Fiber Communication* (Optical Society of America, Washington, D.C., 1986), paper WA4.
10. S.B. Poole, D.N. Payne, R.J. Mears, M.E. Fermann, and R.I. Lam-

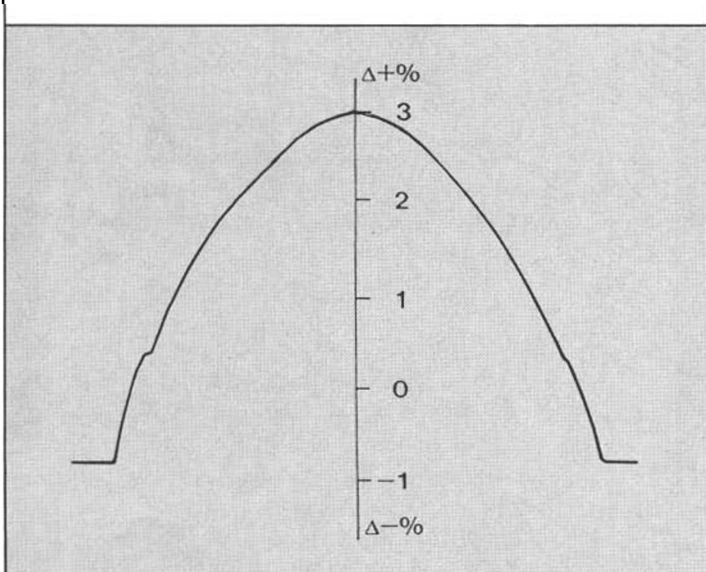



*FIGURE 12. Refractive index profile for 0.4 NA fiber.*

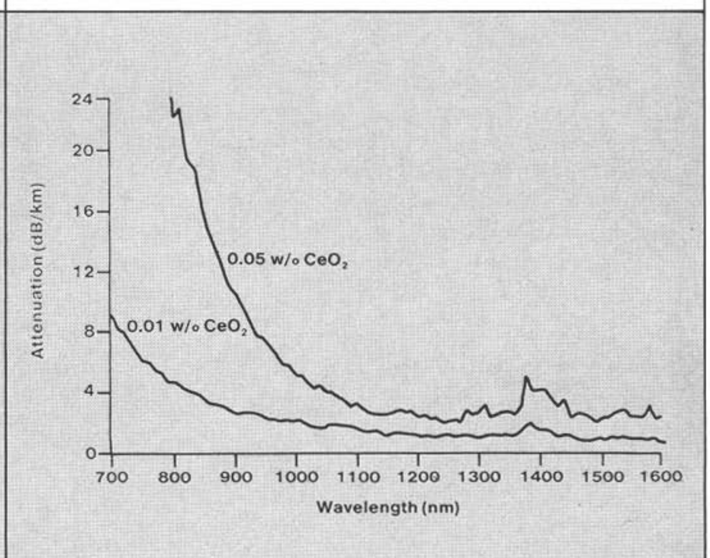
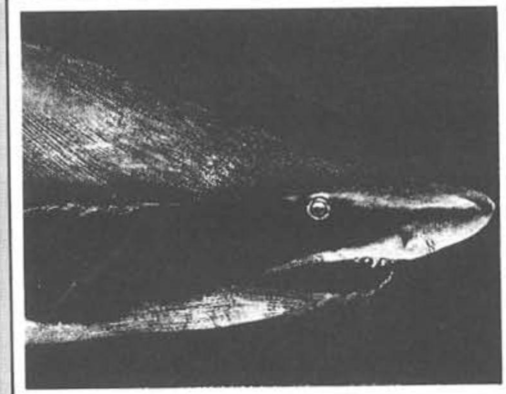



*FIGURE 13. Attenuation of CE-doped multimode fibers made by OVD process.*

ing, "Fabrication and characterization of low-loss optical fibers containing rare-earth ions," J. Lightwave Tech. LT-4, 870–876 (1986).
11. S.B. Poole, Private Communication.
12. L. Reekie, R.J. Mears, S.B. Poole, and D.N. Payne, "Tunable single-mode fiber lasers," J. Lightwave Tech. LT-4, 956–960 (1986).
13. A. Sarhangi and D.A. Thompson, "Chemical vapor deposition of fluoride glasses," ECOC 3, 61–68 (1986).
14. H. Suda and M. Horiguchi, "High-rate synthesis mechanism in the multi-flame VAD method," ECOC 1, 59–62 (1986).
15. K. Okubo, Private Communications (1986).
16. A. Sarkar and T. Merritt, "Design and performance of a hybrid process," *Digest of Conference on Optical Fiber Communication* (Optical Society of America, Washington, D.C., 1985) paper MF1.
17. M. Mikami, K. Kokura, K. Matsubara, and Y. Kamikura, "High strength single mode fiber fully synthesized by new VAD process," ECOC 1, 329–332 (1986).
18. H. Kawazoe, M. Ogai, H. Hiramatsu, and N. Sato "High speed production of GI fiber," Inter. Wire & Cable Symposium 421–425 (1986).
19. H. Murata, "Recent developments in vapor phase axial deposition," J. Lightwave Tech. LT-4, 1144–1150 (1986).
20. H. Kanamori, H. Yokota, G. Tanaka, M. Watanabe, Y. Ishiguro, I. Yoshida, T. Kakii, S. Itoh, Y. Asano, and S. Tanaka, "Transmission characteristics and reliability of pure-silica-core single-mode fibers," J. Lightwave Tech. LT-4 1144–1150 (1986).
21. H. Yokota, H. Kanamori, G. Tanaka, S. Tanaka, and S. Suzuki, "Fabrication of dispersion shifted single-mode fibers with zero dispersion wavelength in 1.5 μm region," Nat'l Com. IECE J. 410, 1–225 (1985).
22. R.B. Brown, Private Communication (1986).
23. R.V. VanDewoestine and A.J. Morrow "Developments in optical waveguide fabrication by the outside vapor deposition process," J. Lightwave Tech. LT-4, 1020–1025 (1986).
24. T.D. Croft, J.E. Ritter and V.A. Bhagavatula "Low-loss dispersion-shifted single-mode fiber manufactured by the OVD process," J. Lightwave Tech. LT-3 931–934 (1985).
25. V.A. Bhagavatula, J.E. Ritter, and R.A. Modavis "Bend-optimized dispersion-shifted single-mode designs," J. Lightwave Tech. LT-3, 954–957 (1985).
26. G.E. Berkey, "Fabrication of 0.4-N.A. fibers by the outside process," *Digest of Conference on Optical Fiber Communication,* (Optical Society of America, Washington, D.C., 1986), paper TuG3.
27. D.A. Thompson, P.L. Bocko, and J.R. Gannon, "New source compounds for fabrication of doped optical waveguide fibers," Proc. SPIE 506, 170–173 (1984).



*(Editor's note: Sharks generally lose their teeth when they bite into something, then grow new ones. Lately, a species known as the crocodile shark has been leaving its teeth behind in sections of AT&T's undersea lightwave cable system. The following technical memorandum, prepared by AT&T Bell Laboratories, describes how AT&T researchers used these souvenir teeth in the development of a fishbite protected cable to deal with future shark attacks.)*

In September 1985, AT&T installed the world's first deep-water, repeatered, undersea lightwave cable system linking two of the Canary Islands. The undersea system, known as the SL Undersea Lightwave System, is a large capacity, digital fiber optic transmission system capable of spanning the world's largest oceans.

On October 17, 1985, system monitors indicated that the power transmission in the cable had been grounded to the sea along the route. The optical data transmission line, embedded within the steel wire strength member of the cable, was not damaged. A cable ship was dispatched to repair the system and return the damaged section to AT&T Bell Laboratories for diagnosis. Examination of the section revealed that a shark's tooth had penetrated through the polyethylene insulation. Similar types of faults occurred on