2005 | VOLUME 10

gl guide lines

Multimode Fiber

And the Vapor Deposition Manufacturing Process
Outside Vapor Deposition vs. Inside Vapor Deposition

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The bandwidth-link length capability of 50/125 µm multimode fiber has steadily improved over the last several years, to the point where fibers with an effective modal bandwidth (EMB) of 2000 MHz.km at 850 nm – often called OM3 fibers, per the ISO 11801 designation – are becoming a primary consideration for all new premises builds. With this rapid increase in modal bandwidth capability, many industry papers have been published evaluating various multimode fiber manufacturing methods, and their suitability for producing OM3 fibers. High EMB fibers are delivered when the manufacturer maintains close control over the core refractive index profile and accurately measures the finished product's laser bandwidth.

Optical fiber manufacturing traces its origins to the work of Dr. J. Franklin Hyde, an organic chemist at Corning's Sullivan Park Laboratories in the 1930s. Dr. Hyde's experimentation with vaporized liquids led to a process for producing a nearly pure silica compound, called the vapor deposition process.[i] In the late 1960s and early 1970s, Corning scientists Donald Keck, Bob Maurer and Peter Schultz (Figure 1) developed two new optical fiber manufacturing methods derived from Dr. Hyde's process: outside vapor deposition (OVD) and inside vapor deposition (IVD). These two methods remain the foundation of all multimode fiber manufacturing today. Variations of the IVD process exist according to their deposition and consolidation techniques, either through an external flame, as in modified chemical vapor deposition (MCVD), or through a plasma arc, as in plasma chemical vapor deposition (PCVD). Corning-invented technologies are the basis for all glass fiber manufacturing processes worldwide.

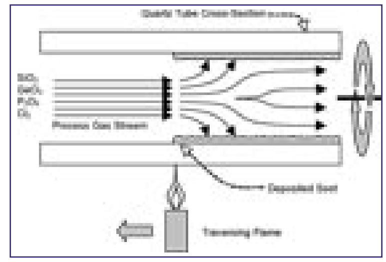
Figure 1: Corning scientists Donald Keck, Bob Maurer and Peter Schultz

i. Dr. Hyde's experimentation included both silicones and high purity fused silica; the latter would be used by Corning to create numerous products including spacecraft windows, optical lenses, telescope mirrors, and optical fiber. Hyde was inducted into the National Inventors Hall of Fame in 2000. For more information on the history of Corning innovation, visit www.corning.com/discovery_center.

The governing physics for core preform manufacturing is basically the same between OVD and IVD. For both processes, the essential manufacturing steps are deposition, drying, sintering (or consolidation), and centerline closure.

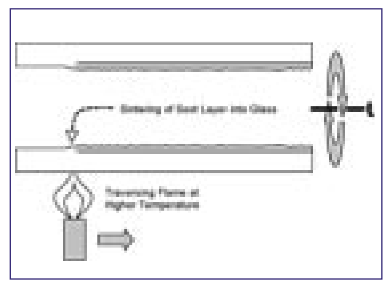
Modified Chemical Vapor Deposition – MCVD

MCVD was initially reported by Bell Laboratories in 1973[ii]. MCVD preform manufacturing uses a glass tube as the basis for vapor deposition, where raw chemical materials are oxidized into a stream of silica and germania vapor flowing through the tube. Additional process gases are included in the process stream to facilitate drying and centerline closure. The tube itself is mounted onto a rotating lathe, and an external flame moves transversely along the length of the tube, creating a hot/cold interface on the internal wall. This hot/cold interface initiates the capture of soot particles on the tube wall through a mechanism called thermophoresis, which is the tendency of particles to migrate down temperature gradients (Figure 2). The external flame temperature is then increased to sinter the soot into a consolidated glass before deposition of the next soot layer (Figure 3). This laydown process is repeated layer-by-layer to build a finished optical fiber preform, which is then ready for centerline hole closure and further processing prior to fiber drawing (Figure 4).



(See Appendix A)
Fig 2: MCVD soot deposition.

For high-bandwidth multimode fibers, the MCVD process poses many challenges to be overcome. In order to attain 2000 MHz.km EMB (or higher), the multimode graded index profile must be smooth and uniform along the axial fiber length, and profile perturbations must be minimized to realize high laser bandwidth.



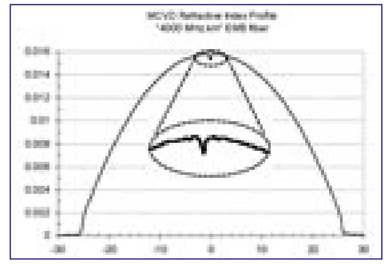
(See Appendix B)
Fig 3: MCVD preform consolidation.

A completed MCVD preform will have a large hole remaining at the centerline relative to OVD, making it prone to centerline dips following hole closure. In any IVD process, the hole is closed with the preform in a horizontal position. The preform is externally heated, and a combination of surface tension and centerline vacuum are used to shrink/close the hole. During this process, germania depletion on the centerline is a concern for IVD processes, due to the intense heat and time required to collapse the centerline hole.

(See Appendix C)
Fig 4: Finished MCVD preform ready for centerline closure.

Historically, this vulnerability has been widely noted, even by the strongest proponents of MCVD manufacturing[iii]. Since the introduction of the IEEE 802.3z gigabit Ethernet standard, leading MCVD manufacturers have made some gains in profile smoothness at the centerline, but the fundamental challenges of MCVD manufacturing remain.

In 2004, Corning Optical Fiber sampled several high-bandwidth multimode fibers from a leading MCVD manufacturer, with advertised 10 Gb/s link length performances of 150, 300 and 500 meters at 850 nm, and found that approximately half of the fibers tested exhibited a dip at the core centerline, and all had centerline tuning errors[iv] (Figure 5).



(See Appendix D)
Fig 5: MCVD graded index profile.

Another key challenge for MCVD manufacturers is maintaining bandwidth uniformity along the length of the fiber preform. In order to maintain axial bandwidth uniformity, process gas flow must be maintained at a steady state throughout preform manufacturing, and soot must be uniformly deposited along the entire length of the IVD silica tube. The soot transport in an MCVD process may be impacted by entry effects, tube blockages, tube diameter fluctuations, or tube exhaust turbulence. Surface temperature uniformity is extremely important during deposition, as even slight variations will lead to compositional variations in the preform. In an MCVD process, deposition temperatures are much higher than in the OVD process. This, combined with the fact that glass has a higher thermal conductivity than soot, makes the MCVD process prone to variable axial temperature gradients during deposition, potentially leading to axial bandwidth non-uniformities.

The MCVD tendency toward axial non-uniformity may be further compounded by geometry variations in supplied third-party tubes. Unlike OVD, MCVD manufacturers must rely heavily on the quality of their tube suppliers, where even small variations in tube thickness or tube bow can lead to compounding axial uniformity errors during preform manufacturing. In 2004, Corning measured a number of high-bandwidth 50/125 µm MCVD fibers with EMB between 950-4000 MHz.km, first on a long 8.2 km length and then on both 4.1 km halves of the original fiber length. These measurements revealed

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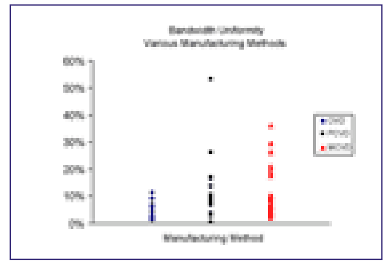
ii. MacChesney, O'Conner, Simpson, and DiMarcello, "Multimode optical waveguides having a vapor deposited core of germania doped borosilicate glass," American Ceramic Society Bulletin, pp 52 and 704, 1973.

iii. "Modified chemical vapor deposition preforms typically exhibit a center dip in the refractive index profile." – Nagel, MacChesney & Walker (Bell Labs), Optical Fiber Communications Vol 1, Fiber Fabrication, pp 12 and 91, 1985.

iv. A recent study by Bell and Avaya Labs agreed with the Corning results. Their study evaluated a total of 184 preforms from a set of 13 MCVD lathes, and noted that "most fibers have some perturbations in the index profile at the center." However, when attempting to predict bandwidth from preform refractive index profile measurements, the authors chose to eliminate values near the centerline, stating that "near 0, the manufacturing process induces certain glass characteristics that can affect light transmission in ways that affect refractive index measurements but not fiber bandwidths." – Golowich, Landwehr, and Vander Weil, "Interplay Between Physics and Statistics for Modeling Optical Fiber Bandwidth," Technometrics, pp 215 – 229, August 2002.

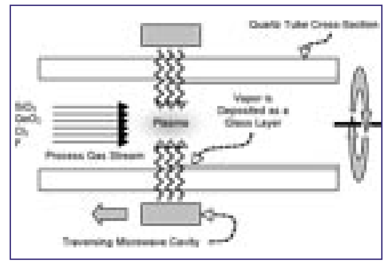
an average of 13% difference in EMB between the 4.1 km halves, revealing remarkable axial non-uniformity along the fiber length. The data is shown in *Figure 6*, alongside similar data from PCVD and OVD processes (which will be discussed).



(See Appendix E)
Fig 6: Bandwidth uniformity by manufacturing method.

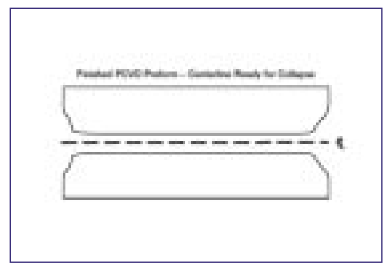
This means that fiber lengths of a few hundred meters – the length typically found in an enterprise network – may well be significantly lower than the length characterized at the fiber manufacturing plant. This degree of EMB non-linearity after an IVD fiber is cut into shorter lengths may introduce considerable system risk in high-performance multimode fiber applications.

Plasma Chemical Vapor Deposition – PCVD



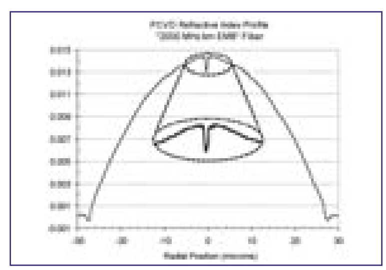
(See Appendix F)
Fig 7: PCVD soot deposition/sintering.

PCVD was first described by Philips Research Laboratories in 1976[V]. PCVD preform manufacturing is overall very similar to MCVD, where raw materials are introduced as a process gas stream into a third-party glass tube. In PCVD, however, the vapor deposition and consolidation occurs as part of the same step, and is activated by internal plasma instead of an external flame. The plasma is created by a traversing microwave cavity (Figure 7). As with MCVD, the completed PCVD preform will have a centerline opening remaining in the completed preform (Figure 8).



(See Appendix G)
Fig 8: Finished PCVD preform ready for centerline closure.

Refractive index profile measurements of PCVD-manufactured fibers often demonstrate a vulnerability to centerline dips, even in 50/125 micron fibers sold with high EMB specifications (Figure 9). Notably, in the described 2004 experiment Corning measured the refractive index profiles of a number of PCVD-manufactured multimode fibers and found their centerline performance to be better than comparative MCVD-manufactured fibers (Figure 10). This highlights the importance of quality manufacturing and engineering, which will be discussed again later.

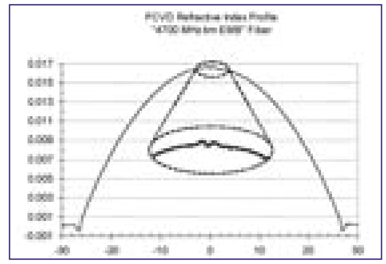


(See Appendix H)
Fig 9: PCVD graded index profile

Significantly, however, PCVD-made multimode fibers are vulnerable to the same bandwidth non-uniformity along the fiber length as those made from the MCVD process. Again, Corning measured the EMB values on an 8.2 km length of PCVD-made fiber, then cut the fiber in

v. Geittner, Kyppers, and Lydtin, “Low-loss optical fibres prepared by plasma-activated chemical vapor deposition (CVD),” Applied Physics Letters, pp 28 and 645, 1976.

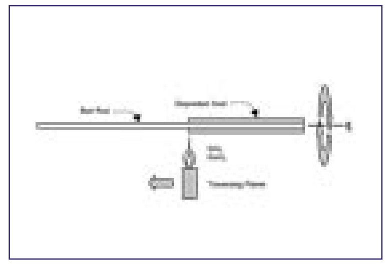
two halves and measured each remaining 4.1 km length. The average difference in EMB from the originally measured value was 14%, or almost exactly the same variability as found with the MCVD-made fibers (Figure 6).



(See Appendix I)
Fig 10: PCVD graded index profile.

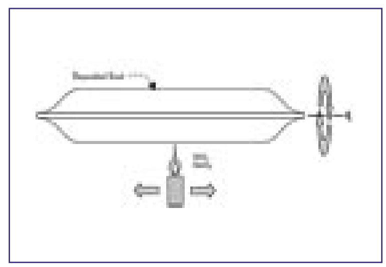
Outside Vapor Deposition – OVD

Corning's production optical fibers are manufactured using the OVD process. In OVD, a bait rod is used to capture soot from traversing process gases, and the optical fiber preform is constructed by accumulating sequential layers of soot from the center outward (Figures 11 and 12).



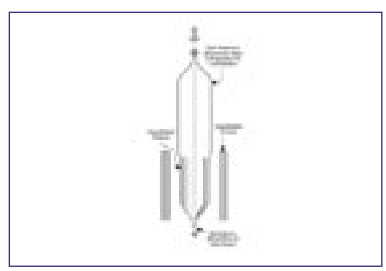
(See Appendix J)
Fig 11: OVD Core Laydown.

Note that the OVD process enables the process gas stream to contain only silica and germania, whereas other processes, like MCVD, must use additional chemicals to facilitate soot consolidation, and centerline hole closure. The MCVD use of phosphorous (P_2O_5), in particular, has been linked to increased attenuation in the presence of radiation and overall higher lifetime hydrogen aging.[vi,vii]



(See Appendix K)
Fig 12: Laydown Continues.

In the OVD process, the soot preform is transferred to a consolidation furnace for cleaning and drying. After drying is completed, the soot preform is sintered as part of the same process step, ensuring no recontamination of the glass is possible. The preform is consolidated into pure glass in a stable, precisely controlled environment to ensure physical uniformity in the preform. Finally, the centerline of the preform is exposed to an etch gas prior to hole closure to ensure that the centerline will be smooth and compositionally uniform (Figure 13). The advantage of the OVD process in centerline hole closure, resulting in a more accurate index profile, is widely accepted and has been consistently reported since the inception of the optical fiber industry. [viii,ix]



(See Appendix L)
Fig 13: OVD Consolidation Process.

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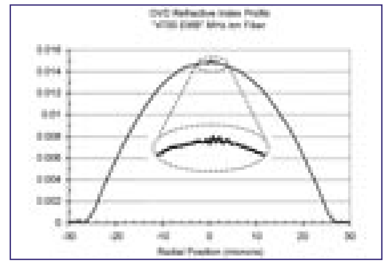
vi. Noguchi, et al., Journal of Lightwave Technology., LT-3, pg 236, 1985.

vii. Rush et al., British Telecom Technology Journal, 2 (4), pg. 84, 1984.

viii. "...index depression at the axis of the fiber... is not a feature of the OVD process" – Morrow, Sarkar, & Schultz (Corning), Optical Fiber Communications Vol 1, Fiber Fabrication, pp 12 and 91, 1985.

ix. In an interview with a local newspaper in Worcester, MA, Daryl Inniss of RHK Inc., commented on the centerline challenges faced by MCVD manufacturing engineers. He was quoted as contrasting the performance of MCVD to OVD by saying "...other companies, such as Corning Inc., use a different process and didn't have to overcome the center dip." – Esposito, "OFS saw value of key preform process," Worcester Telegram & Gazette, February 25th, 2005.

Throughout the process, Corning uses proprietary manufacturing techniques to ensure that fibers made from the OVD process will have the smooth, uniform refractive index profiles needed for high-performance multimode fibers (Figure 14).



(See Appendix M)
Fig 14: OVD graded index profile.

One of the major advantages of the OVD process is the ability to manufacture glass with very high purity levels. The glass is formed directly from the chemical raw materials, unlike IVD methods that are formed on a glass tube manufactured by a third-party supplier. The drying process is a very important step in achieving low levels of glass impurities. Unlike IVD processes, the OVD process optimizes time, temperature, and process gas concentrations to deliver preforms with ultra low impurity levels.

Finally, the inherently stable OVD process yields fibers that have the most consistent EMB uniformity in the industry. Corning fibers in the mentioned 2004 experiment averaged only 5% change in bandwidth after cutback, which is within normal bandwidth measurement variability and is considered when fibers are selected for shipment. Corning has spent many years investigating bandwidth uniformity, and ensures that every meter of multimode fiber deployed in the field will perform as advertised. After 30 years and millions of kilometers of multimode fiber shipments, 100% of Corning fibers have met the end-user's network bandwidth requirements.

Summary

Corning invented both fundamental multimode fiber vapor deposition manufacturing processes and ran them in parallel for over 15 years to fully understand the capabilities of each. Corning ultimately chose OVD technology for optical fiber preform manufacturing, which offers exceptional uniformity, smooth refractive index profiles, and full quality control from raw materials to finished product. In addition, Corning has invested significant resources in engineering, prototyping, and fabricating improvements to this technology over the last 30 years.

Ultimately, however, end-users do not purchase manufacturing processes for their optical networks – they buy cabled optical fiber. When considering the pertinence of optical fiber manufacturing with high-performance premises networks, the variables to consider may be reduced to three relevant items:

1. The fiber must have a well-controlled graded index profile. OVD, coupled with Corning's unrivaled expertise in optical fiber manufacturing, results in the most accurate profiles in the industry.

2. The fiber must be made by a high-quality manufacturer with the engineering expertise to make uniform, smooth graded index profiles. Corning stands alone in this regard, with over 30 years of optical fiber manufacturing experience and continued registration with ISO 9001 and TL-9000 quality standards. Corning is also the only optical fiber manufacturer to have received the Malcolm Baldrige National Quality Award, the most prestigious quality award in the United States.

3. The fiber must be accurately measured for laser bandwidth to ensure field performance with all multi-Gb/s application standards. Corning is the only optical fiber manufacturer that measures laser bandwidth performance on every meter of every reel without sampling or outsourcing to third-party laboratories. Corning measures laser bandwidth performance in accordance with the test procedures specified in TIA/EIA 455-204/220 and IEC 60793-1-41/49, and uses the industry's newest, most accurate minimum calculated Effective Modal Bandwidth (minEMBc) measurement to predict high-bandwidth multimode fiber performance. MinEMBc is the only high-bandwidth, DMD-based measurement that is inherently scalable to predict multiple bit rates and link lengths, where other methods provide only a pass or fail estimation for 10 Gb/s over 300 meters.x

Corning leads the market in the continued evolution of high-performance 50/125 µm multimode fiber. Our unrivaled experience and expertise in optical fiber manufacturing makes Corning InfiniCor fibers the most trusted laser-optimized fibers in the industry.

Contributing Authors

David Velasquez, Global Product Line Manager, Premises Fibers

Peter Ronco, Manager, Vapor Deposition Engineering

x. For more information regarding Corning's industry-leading laser bandwidth measurements, please visit http://www.corning.com/opticalfiber/products__applications/products/infinicor.aspx

Appendix A

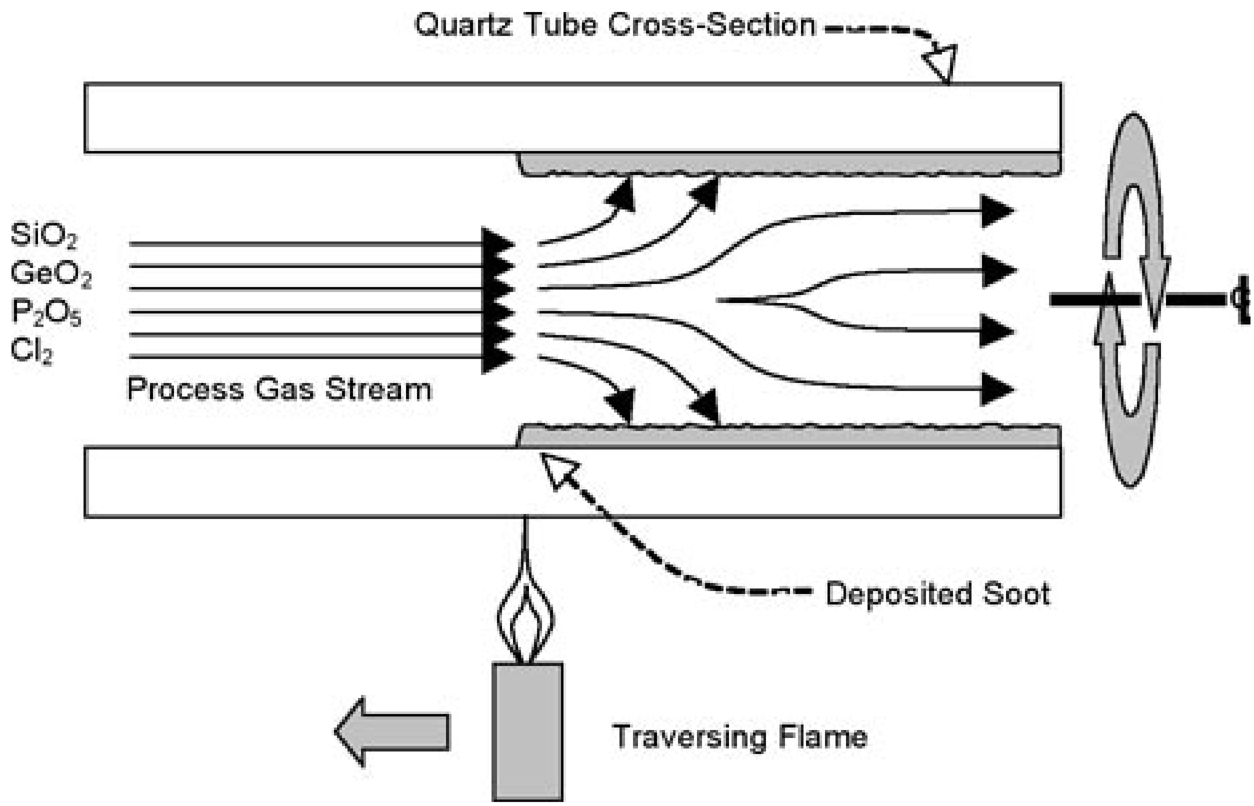


Figure 2: MCVD soot deposition.

Appendix B

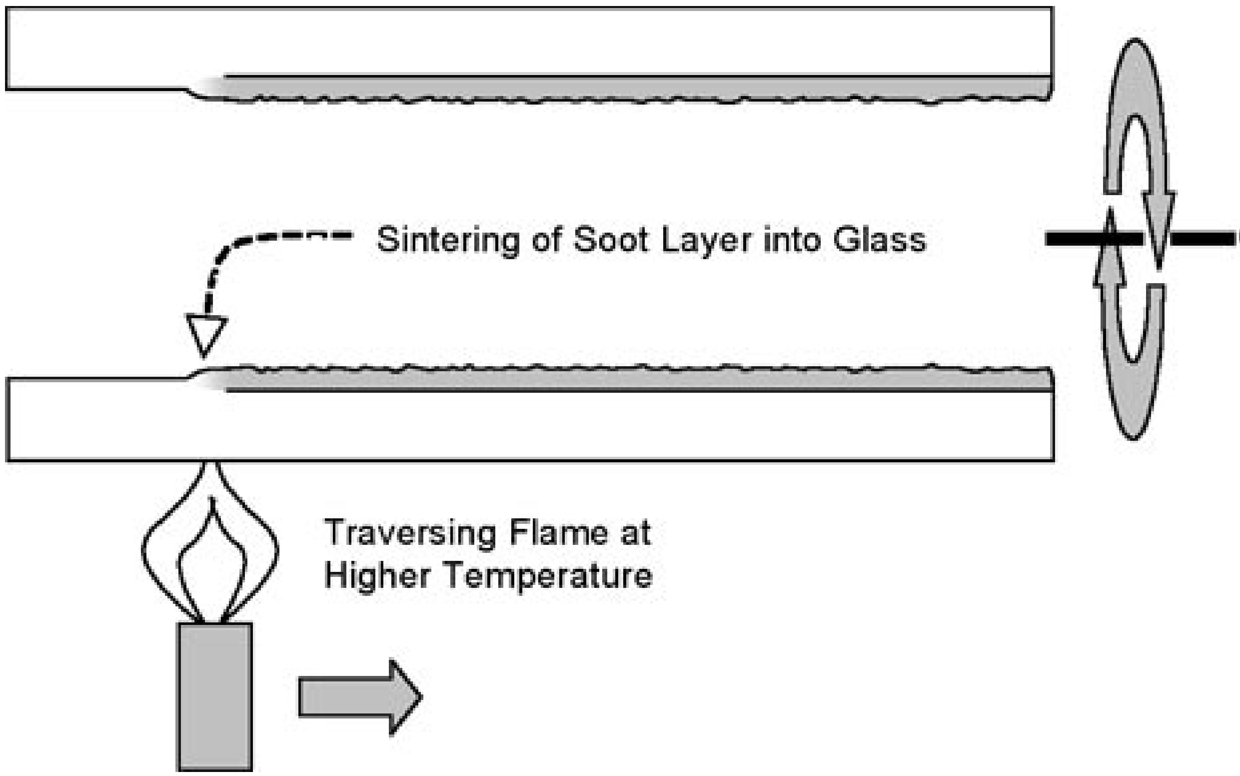


Figure 3: MCVD preform consolidation.

Appendix C

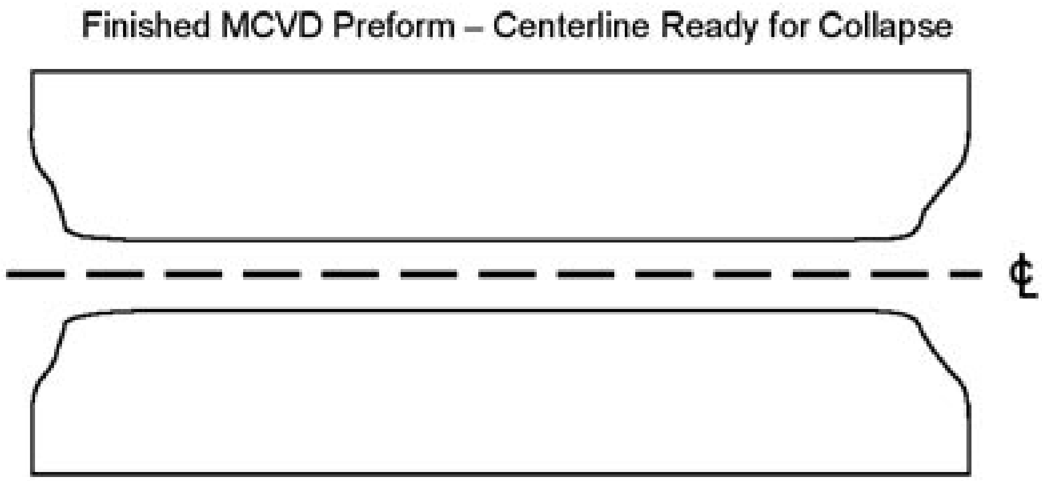


Figure 4: Finished MCVD preform ready for centerline closure.

Appendix D

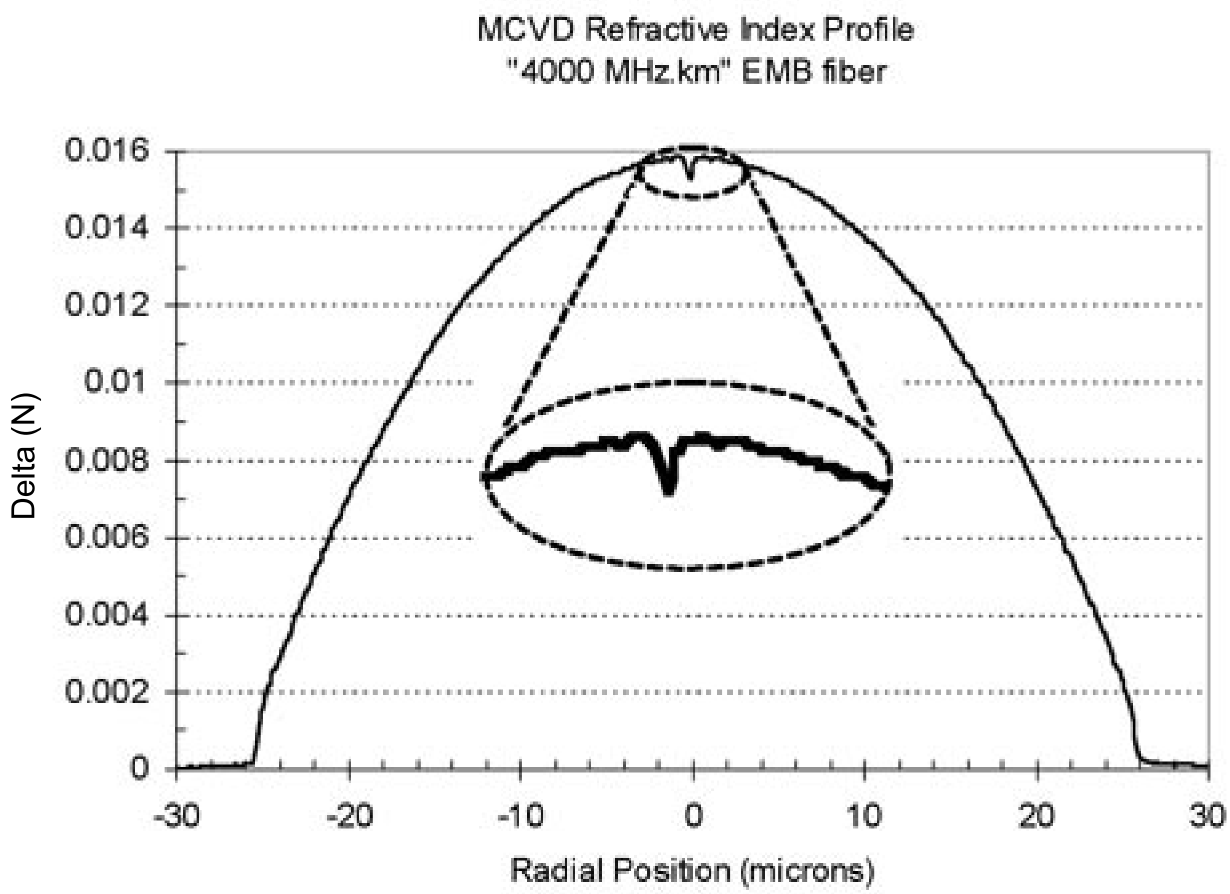


Figure 5: MCVD graded index profile.

Appendix E

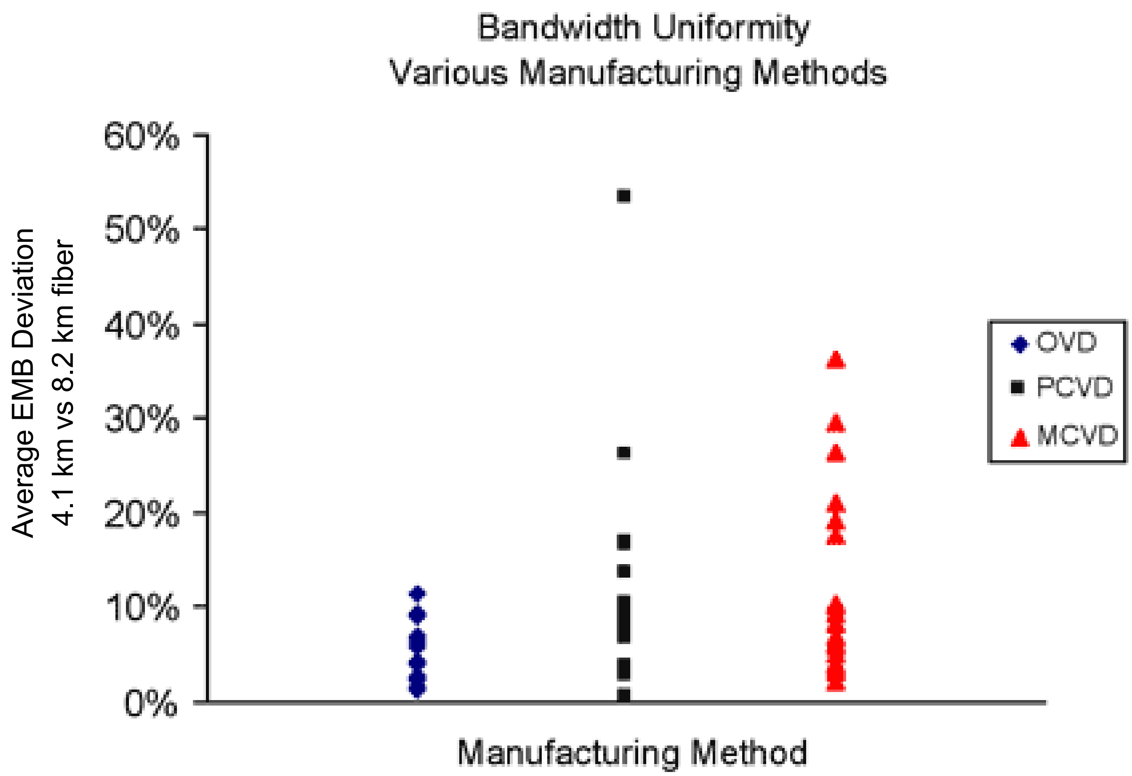


Figure 6: Bandwidth uniformity by manufacturing method.

Appendix F

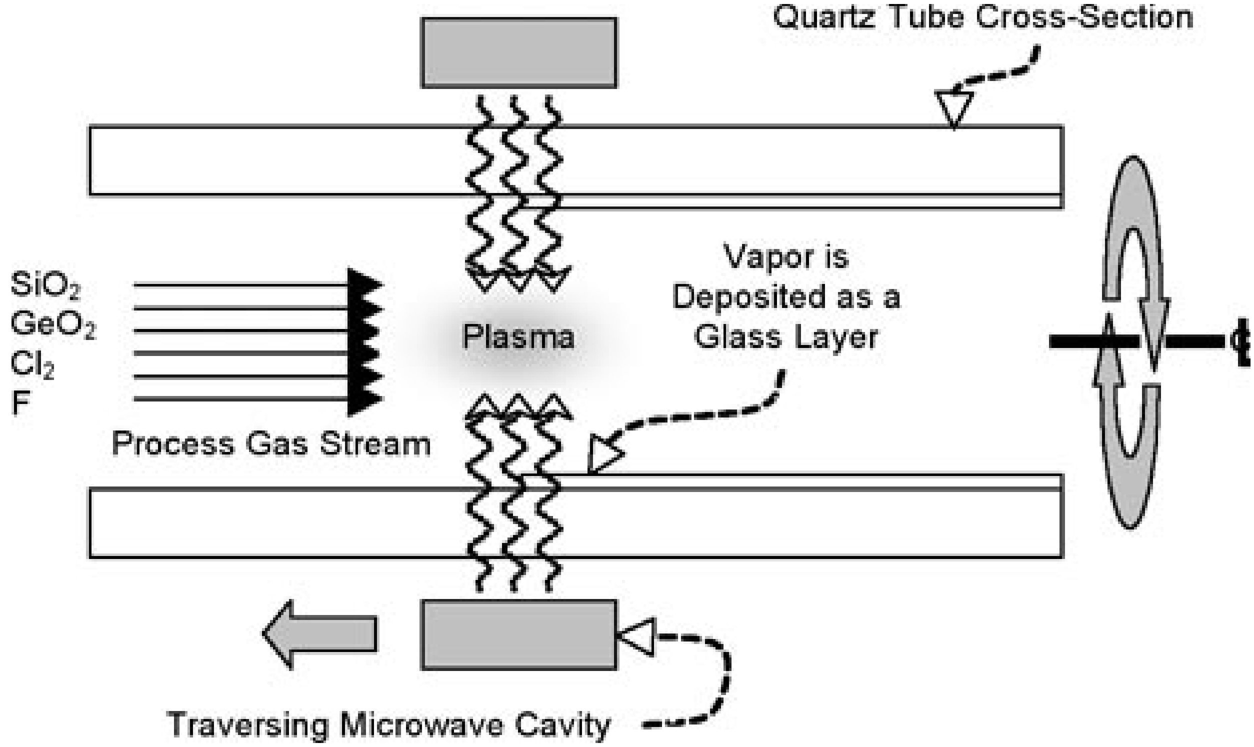


Figure 7: PCVD soot deposition/sintering.

Appendix G

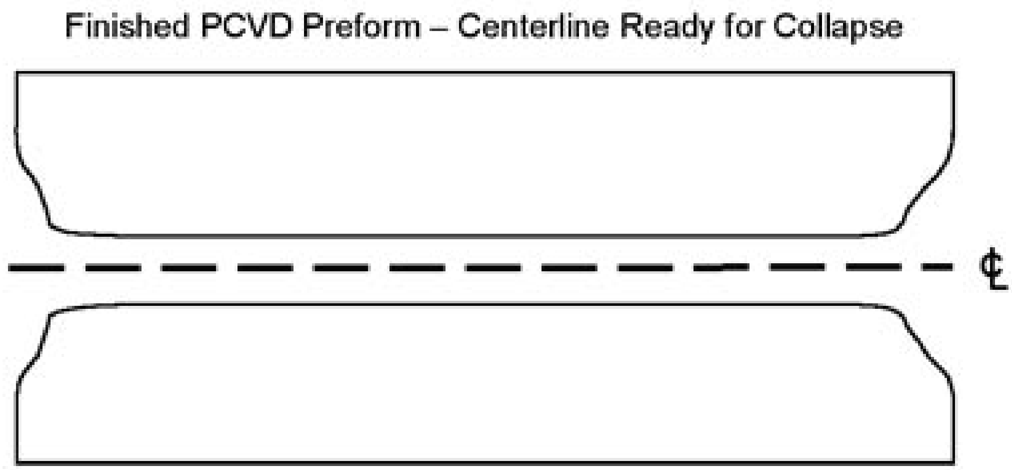


Figure 8: Finished PCVD preform ready for centerline closure.

Appendix H

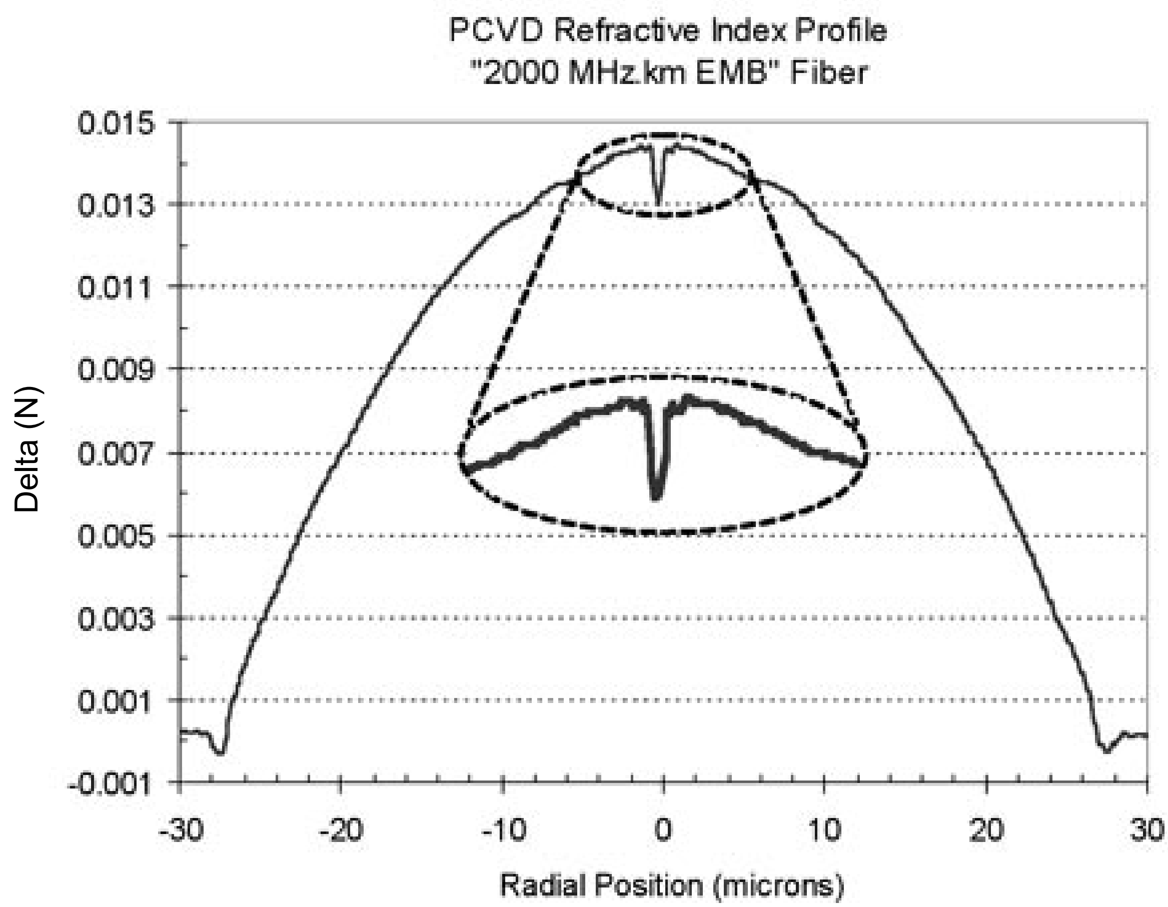


Figure 9: PCVD graded index profile.

Appendix I

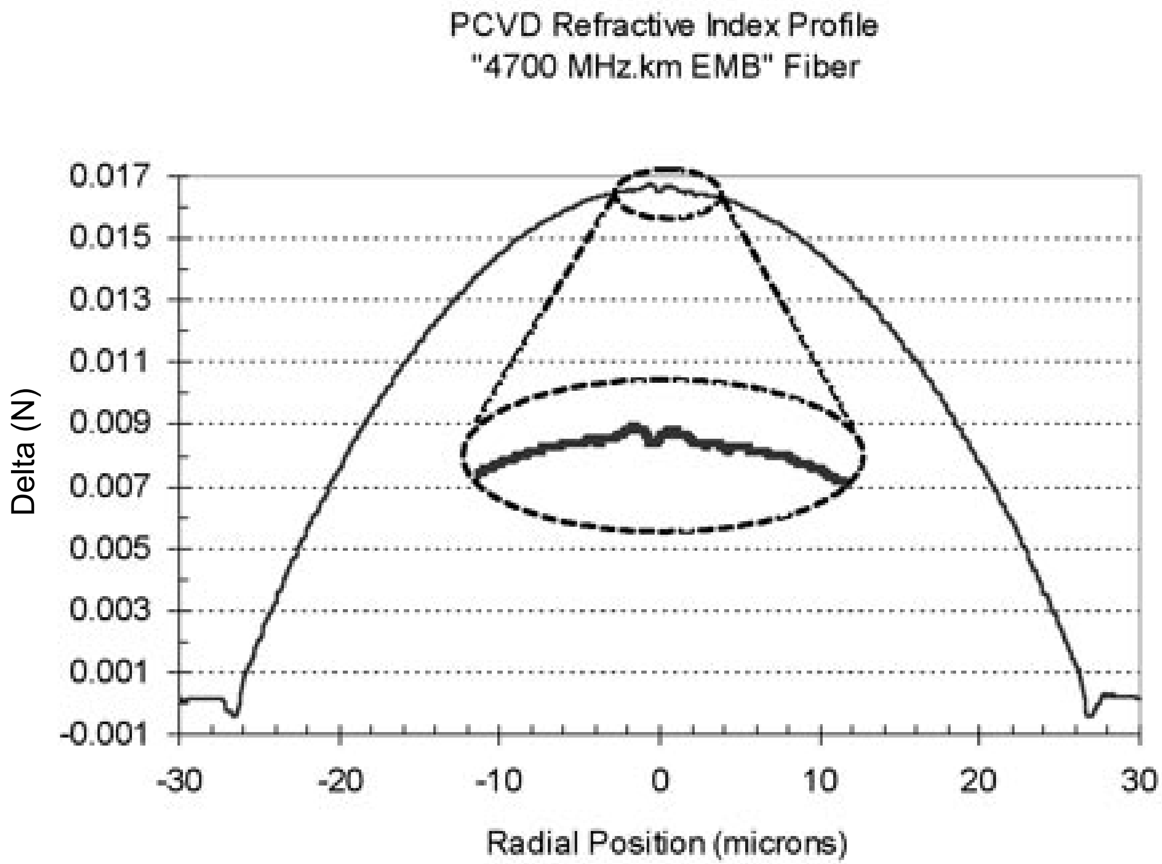


Figure 10: PCVD graded index profile.

Appendix J

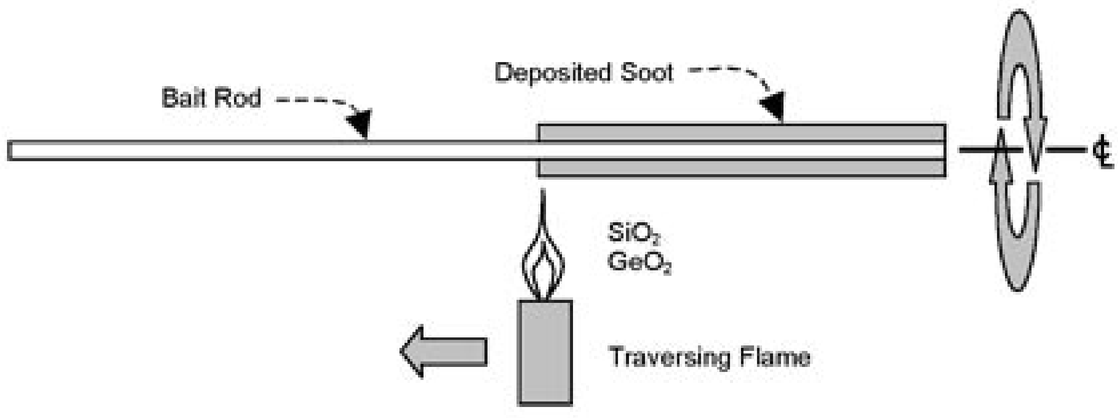


Figure 11: OVD Core Laydown.

Appendix K

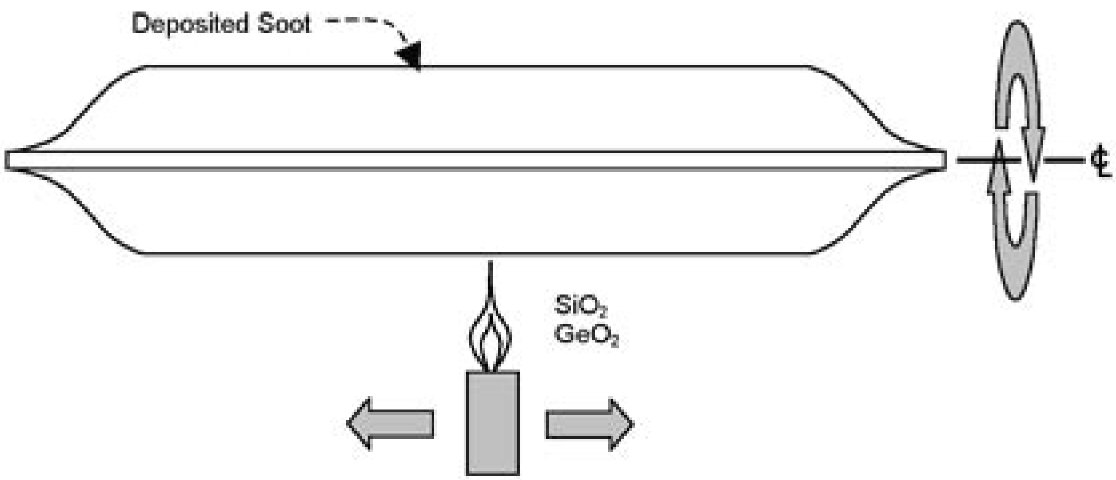


Figure 12: Laydown Continues.

Appendix L

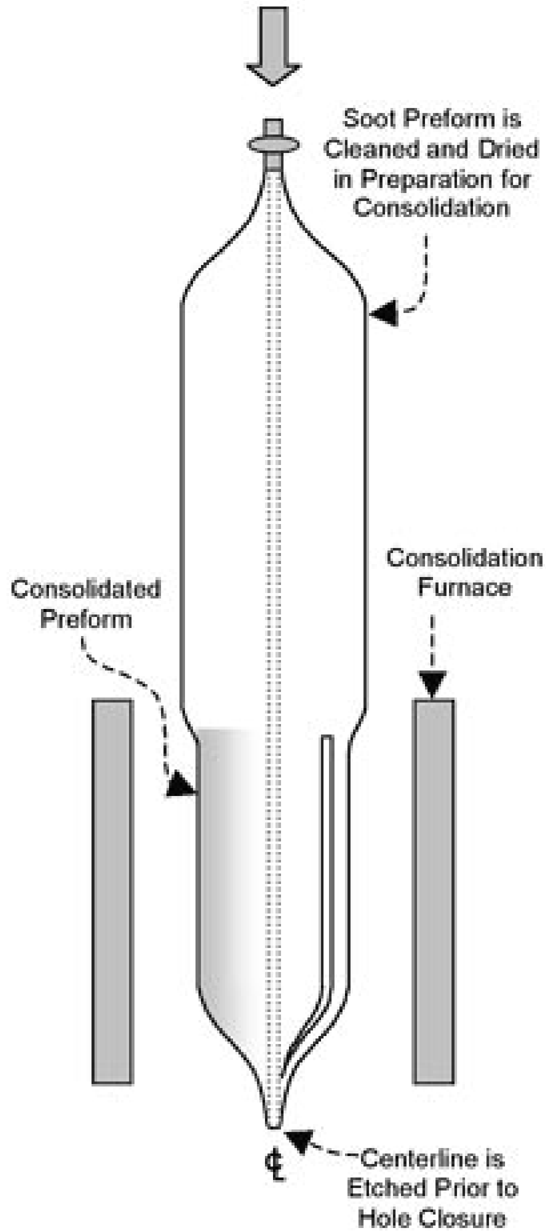


Figure 13: OVD Consolidation Process.

Appendix M

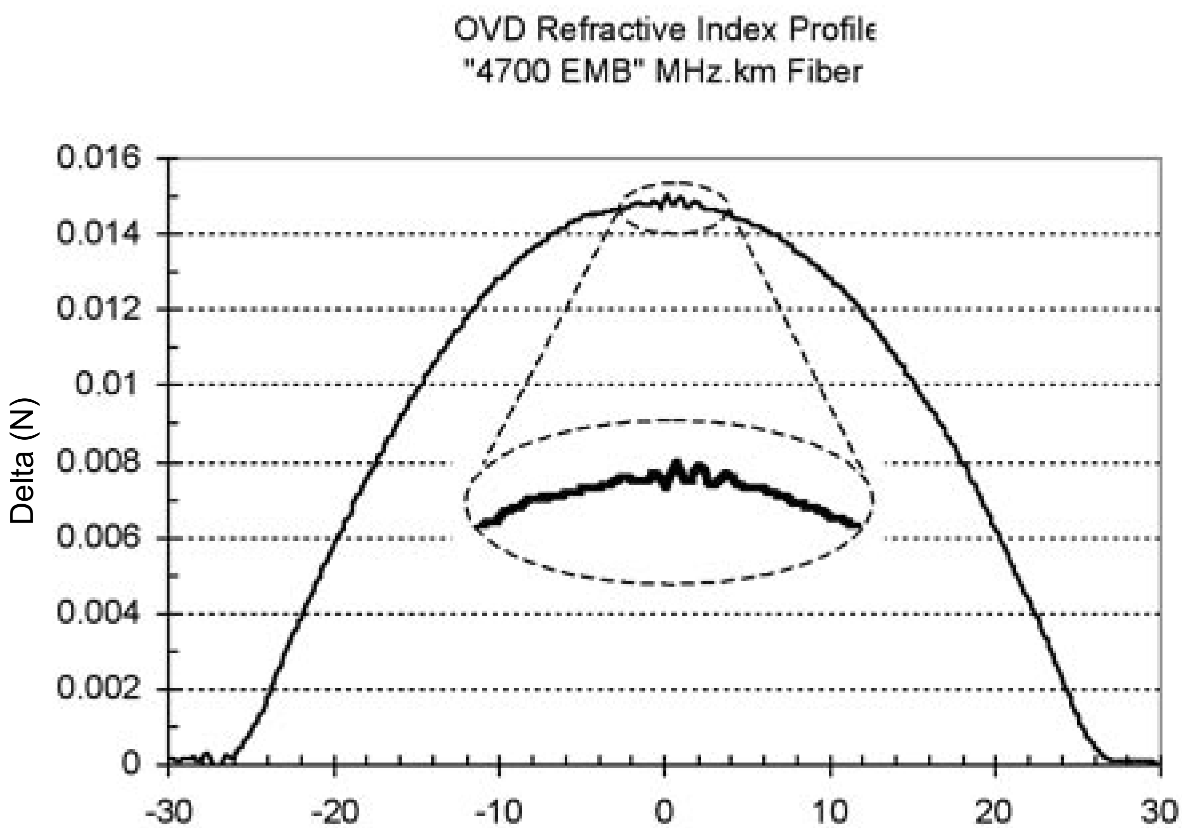


Figure 14: OVD graded index profile.