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SECOND WORKSHOP ON
OPTICAL FIBRE COMMUNICATION
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FABRICATION TECHNOLOGY OF OPTICAL FIBERS

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CONTENTS

Introduction

This presentation is concerned basically with general concepts of the technology of optical fiber fabrication. Since propagation theory concepts will be explored in other presentations during the Workshop, these are not explored here.

Even though there is a variety of optical fibers being commercialized today for all different applications, it is assumed that only fibers for telecommunications are being considered.

The presentation has been divided in 2 main parts: Choice of Materials and Manufacturing Process. In the first part, a series of considerations are made to justify the choice of silicate glasses for the fabrication of optical fibers. This choice proved itself to be adequate as demonstrated today by the successful operation of commercial optical communication systems throughout the world, which strongly depend on the performance of these materials.

Following these considerations, the main details of the manufacturing process itself are described. In this part attention was concentrated in the 2 most powerful methods for manufacturing optical fibers, avoiding this way to waste the limited time of the presentation in other methods.

1. CHOICE OF MATERIALS

The choice of silicate glasses for the manufacturing of optical fibers is based on a series of properties of these materials which make them best suited for this specific application. These properties are discussed in this chapter.

As the transmission medium of a communication system, an optical fiber has to perform three main roles: it has to be a waveguide in the optical spectrum, have low optical loss and offer reasonable physical durability.

1.1 Optical waveguide

The characteristic of guiding optical waves imposes a material structure which is based on a simple principle of Physics, Total Internal Reflection. As shown in figure 1, the basic construction of an optical fiber consists of a cylindrical nucleus,or core, surrounded by a cladding of smaller index of refraction. The difference in indices is a necessary condition for the guidance of waves along the nucleus of the fiber.

An optical fiber, therefore, has to be fabricated of at least two different materials with different indices of refraction.From the process technology point of view, this immediately implies further restrictions on the choice of adequate materials due to the necessary physical compatibility between them. The creation of an interface at the core-cladding boundary may result in serious thermo-mechanical and rheological problems if the two materials behave too differently when subjected to temperature gradients. It is necessary, therefore, to have control of the coefficient of thermal expansion and viscosity of the materials.

The geometrical dimensions of an optical fiber are imposed by the practical viability of telecommunication systems, involving kilometer lengths and high flexibility for cable manufacturing and installation, and by the compatibility with optical sources and detectors, to which the fibers are physically connected. These restrictions necessarily bring the outside diameter of an optical fiber to a few tenths of a millimeter (125 microns has been defined as the international standard).

Few materials have the capability of allowing simultaneously the control of its index of refraction, viscosity and coefficient of thermal expansion and still be able to be manufactured in 125 micron fibers for kilometer long lengths. Actually, aside from oxide glasses, presently known technology offers as alternatives only certain plastic polymers and fluoride glasses. These materials are still in a R&D stage though, with serious problems to be overcome such as low chemical durability and high optical losses.

Silicate glasses, having S_iO_2 (silica) as a matrix and other oxides as modifiers, were the first candidates for the manufacturing of optical fibers since this new field of technology was started 20 years ago. Aside from the fact that a considerable amount of data had already been collected about these glasses putting them at that time ahead of other material candidates, silicate glasses offer the remarkable characteristic of allowing for a large variation of its physical properties by the selected addition of oxide modifiers to the basic silica structure. This characteristic proved itself to be valuable when one considers the variety of profiles in index of refraction that could be tested, allowing for the choice of optimized transmission characteristics in optical fibers being manufactured presently.

The basic waveguide structure, as mentioned before, requires a core in the fiber with a higher index of refraction than the cladding. Further considerations regarding the optimization of transmission properties involve the necessity of controlling the change in refractive index of the matrix silica structure both in the positive and negative directions. Figure 2 shows the most commonly used oxide additions and their respective effects on the index. Fluorine (F) and Boron Oxide (B_2O_3) have been the dopants used for decreasing the index. In the most recent years Boron Oxide has been avoided due to some of its negative side properties of low chemical durability and relatively high attenuation losses. The most common dopant for increasing the index of silica is Germanium Oxide (G_eO_2). Optical fibers being commercialized presently, both singlemode and multimode, have this oxide as a main dopant even though it is relatively very expensive as compared to other materials.

The final composition of the glass constituting the core of the optical fiber is a combination of the dopants shown in figure 2, with different mole concentrations. The outer cladding of the fiber is made of pure silica. It is remarkable and very fortunate that silicate glasses can be manufactured with dopant concentrations of up to about 20% of G_eO_2, for example, without having crystallization or phase separation problems. These problems would render the fibers useless for telecommunications due to excessive light scattering and anisotropic effects.

Since the composition of the glass has to be modified in order to change its refractive index, other properties are also changed. Of these, the ones that could most negatively affect the overall behavior of the fibers during and after fabrication are the coefficient of thermal expansion and the viscosity. If the viscosities of the doped glasses which constitute the core of the fiber were higher than that of pure silica at the melting temperature it might not be possible to manufacture the fiber due

to adverse flowing conditions. Again, silicate glasses offer unusually favorable properties in that sense, since pure silica glass has a much higher viscosity than any of its doped compositions.
The thermal expansion of the core and cladding of the optical fiber, as mentioned before, have to be adequately matched in order to avoid the mechanical failure of the whole structure as a consequence of internal stresses. The change in expansion coefficient as a function of composition, shown in figure 3, is sufficiently small to avoid this problem. Aside from that, an extra benefit derives from the use of silicate glasses in optical fibers having doped silica as core and pure silica as cladding. As shown in the figure, pure silica has a smaller expansion coefficient than its doped compositions. The consequence of this configuration is that the residual stresses present in the fiber after cooling down during manufacturing is such that the core will be subjected to tension while the outer cladding is subjected to compression. From the mechanical point of view this situation is ideal, since it contributes positively to the strength of the fiber.

1.2 Optical loss

The choice of silicate glasses for the manufacturing of optical fibers was also strongly influenced by the well known transparency of these materials in the visible and near infrared spectrum of radiation.

But the best glasses commercially available in the late 60's showed attenuation levels of a few thousand dB/km. For fiber links to be viable, the attenuation level had to be considerably decreased to prevent the use of an excessive quantity of costly optical repeaters along a telecommunication line.

Optical losses occur due to two main mechanisms : absorption and scattering.

1.2.1 Absorption

Aside from the intrinsic UV absorption caused by the material itself, mainly two types of impurities contribute to optical losses in silicate glasses by absorption: OH^- radicals and transition metal ions. The success of optical fiber technology depended critically on the ability of removing these impurities to the very low levels presently found.

The availability of optical sources combined to the intrinsic lower levels of attenuation in germanium doped silicate glasses have defined a range of wavelengths from 0.8 microns to 1.6 microns as the "transmission window" in optical fibers. As shown in figure 4, a series of overtones and combinational vibrations of OH^- radicals exist unfortunately right in this range. To achieve the current values of attenuation around 0.5 dB/km at 1.3 microns, the concentration of OH^- had to be reduced to the ppb level.

Electronic transitions in transition metal ions also contribute to absorption in silicate glasses. As shown in figure 5, these ions contribute to absorption in a wide range of wavelengths, also within the transmission window of optical fibers. Due to the abundance of some of these ions in crucibles and raw materials conventionally used for melting glasses, this technique had to be abandoned for the manufacturing of optical fibers.

1.2.2 Scattering

Another mechanism for optical loss is light scattering. Aside from gross defects in the waveguide structure, such as air bubbles or discontinuities in the cylindrical geometry of the optical fiber, scattering occurs due to intrinsic factors in the glass structure. Looked at from a microscopic point of view, the silicate glass structure presents composition and density fluctuations which are responsible for Rayleigh scattering. This mechanism of optical loss ultimately represents the minimum possible attenuation in optical fibers.

As shown in figure 6, the combination of all the mechanisms for optical loss define the transmission window where an optical communication system is most efficient.

1.3 Physical durability

One of the main practical problems that had to be overcome regarding the use of optical fibers in commercial telecommunication systems refers to the fact that glasses are known in common day practice as fragile materials. Actually a considerable amount of skepticism was present among the first potential users of these systems which had the preoccupation of relying on a hair thin glass fiber for the transmission of thousands of telephone conversations. A breakage of one of the fibers, which was believed easy to occur, would cause a tremendous problem from the commercial point of view.

The technological challenge of manufacturing kilometer long glass fibers with a tenth of a millimeter diameter and with sufficient strength continuously along its length was a considerable task. Today this problem has been overcome and, as will be discussed later, there are manufacturing techniques which guarantee a minimum mechanical performance which is sufficient for the subsequent handling of the fiber during testing, cabling, splicing and installation in underground or aerial routes.

The common day observation that glasses are weak materials is not totally unfounded. Indeed, glass bottles, windows, etc, break very easily when subjected to mechanical stress. But this is mainly due to the specific behavior of glassy materials of being unable to deform in a plastic regime. Unlike metallic materials, for example, when a glass object is subjected to stress it can only release this stress elastically. The consequence of this behavior is the creation of very large stresses concentrated at points on the surface of the glass, where small defects are present. As shown in figure 7, the end result of one of these defects is to act as a localized amplification factor for the overall stress subjected to the material. Therefore, even though the intrinsic structure of the glass could easily take the stress subjected to it as a whole, a mechanical failure occurs at the point of the defect where much larger effective stresses are present.

To manufacture strong fibers therefore means to preserve the surface of the fibers during manufacturing. When this is done, values of breaking stresses of 400 kgf/mm² are achieved on a routine basis. With this breaking strength, which for a 125 micron fiber corresponds to about 5 kgf, it has been possible to rely on the optical fiber as a transmission medium in much the same way as a conventional copper wire.

After the mechanical strength problem is overcome, silicate glass materials are one of the best known for its chemical durability. Unlike metals, for example, corrosion due to oxidation or attack from common acids is a minor problem in silicates. Actually, the fact that most chemicals are usually stored inside glass bottles is a practical evidence of the chemical durability of these materials.

Even though the optical fibers being commercialized today show reasonably good performance from the chemical and mechanical points of view, laboratory tests have shown that a phenomenon called "static fatigue" can cause mechanical failure in the fiber after it has been installed for service. This mechanism of failure is a combination of microscopic chemical attack at the surface of the fiber and a residual stress existent in the fiber after it is cabled and installed. It is practically impossible to prevent, on a definite basis, the contact of the fiber with minute quantities of chemical agents that could cause microscopic reactions with the glass surface, such as common water. To prevent static fatigue from adversely affecting the lifetime of a transmission line it is important,therefore, to properly design and construct cables that prevent the existence of large residual stresses in the fiber after it is installed. As

shown in figure 8, lifetimes of the order of 100 years can be theoretically predicted as long as the residual stresses in the fiber do not exceed about 150 gf.

2. MANUFACTURING PROCESS

Having chosen silicate glasses as the adequate materials for optical fibers, a manufacturing process has then to be specified in such a way as to achieve a final product as close in performance as theoretically predicted and in the most economical way. In practice, perturbation parameters are always present in such a way as to cause deviations from what is theoretically predicted. This is true even for the simplest characteristics, such as the fiber geometry, which is predicted to have a perfectly cylindrical form but which in real life, of course, shows deviations from this ideal situation. A good manufacturing process is one that optimizes the yield in production maintaining low costs.

2.1 Glass manufacturing

An optical fiber is a hair thin silicate glass fiber with a composite structure of 2 or more components, with low optical loss and manufactured in kilometer lengths. The basic manufacturing problem consists of obtaining glasses that can be further processed in the shape of a fiber with a core of low optical loss surrounded by a lower refractive index cladding.

The most conventional method for manufacturing glasses in general is to fuse raw materials at relatively high temperatures (~ 1500 °C) and shaping the melt to its final desired form while it maintains its fluid liquid-like behavior. An intrinsic problem with the conventional fusion process is that the raw materials used for melting have relatively high concentrations of contaminants. Aside from that, they have to be melted inside a recipient. Even though high purity Platinum (Pt) crucibles can be used as recipients, the diffusion of contaminants from the crucible to the melt is unavoidable. In the case of optical fibers this problem is specifically harmful since the most usual contaminants are transition metal ions. As we have already seen, these ions strongly contribute to increase the attenuation in the glass at the transmission window for optical communication.

An alternative way to obtain oxide glasses consists of oxidizing halides in the vapour state allowing for subsequent condensation of the glassy particles thus formed. As shown in figure 9, both methods have the oxide glass as an end product. But the basic difference between these methods lyes on the fact that in the case of vapour oxidation, the risk of contamination is greatly reduced. This advantage proved itself of extreme value in optical fiber technology, allowing the present attenuation levels of 0.5 dB/km.

For many years attempts were made to purify the raw materials used for fusion and optical fiber manufacturing. But, again, the vapour oxidation process was more successful in that sense. Very fortunately, as shown in figure 10, the vapour pressures of the liquid chlorides from which the optical fiber is manufactured is much higher than that of the possible contaminants. Therefore, by conventional distillation techniques it is possible to achieve extremely high degrees of purity in these raw materials, contrary to the case in solid raw materials. Part of this purification work was already done when optical fiber technology was started due to similar needs in semiconductor manufacturing technology.

2.2 Vapour oxidation process

Optical fibers under commercial production today are manufactured in a 2 step process, the first of which consists of obtaining a glass preform which is subsequently transformed into the fiber itself. The first step, preform manufacturing, is more complex and therefore important from the technological point of view. As shown in figure 11, the preform defines all the basic transmission parameters of the optical fiber to be manufactured from it, except of course, the absolute geometrical dimensions.

There are 2 main vapour oxidation processes used today for manufacturing optical fiber preforms. They basically differ from each other by the relative deposition of glasses in reference to a substrate. In simple terms these processes can be called INSIDE and OUTSIDE vapour deposition.

As shown in figure 12, in one case the high purity glass is deposited on the inner surface of a tube and in the other case it is collected around a central rod. In both cases, as shown in figure 13,vapours of chlorides of silicon ($SiCl_4$), germanium ($GeCl_4$), phosphorous ($POCl_3$) and boron (BCl_3) are obtained by bubbling O_2 through recipients containing these chlorides in the liquid form (except for BCl_3 which is already obtained as a gas). The mixed flow of chlorides and oxygen (O_2) is fed to the region where the substrate is mounted and the chlorides are then allowed to react chemically and form oxide glasses according to the reactions indicated below:

$$SiCl_4 + O_2 \rightarrow SiO_2 + 2Cl_2$$

$$GeCl_4 + O_2 \rightarrow GeO_2 + 2Cl_2$$

$$4BCl_3 + 3O_2 \rightarrow 2B_2O_3 + 6Cl_2$$

$$4POCl_3 + 3O_2 \rightarrow 2P_2O_5 + 6Cl_2$$

2.2.1 Inside vapour deposition

The process for manufacturing a preform using the mechanism of depositing glass inside a substrate has been called Modified Chemical Vapour Deposition (MCVD). The basic set-up, shown in figure 14, consists of a gas flow control unit, a glass lathe with a motorized torch and an exhaust system for the toxic fumes generated by the process. A controlled mixture of chlorides and oxygen is obtained from the gas control unit and is fed into a rotating silica tube held in the glass lathe. When the chlorides reach the region being heated up by the O_2/H_2 torch and are raised to a temperature around 1400 °C, oxidation occurs. As shown in figure 15, the immediate product of the reaction are submicron soot particles of the various oxide glasses of Si, Ge, P and B. These particles are then forced to follow specific trajectories inside the silica tube, governed by a thermoforesis mechanism, in such a way that a considerable quantity end up being collected at the colder inner walls of the tube in the downstream direction. A porous cylindrical layer of interconnected particles is then formed inside the tube with an average composition defined by the relative amounts of chlorides present in the gas stream. This layer is then sinterized by the passage of the torch leaving a thin (~ 10 micron) vitrified film adhered to the inner surface of the tube. This deposition process is maintained homogeneously along the whole length of the tube in its downstream direction. When the torch reaches the end of the tube its traversing direction is automatically reversed bringing it back to the same starting point upstream. Since the reverse speed of the torch is considerably faster than the deposition speed, the substrate tube temperature during this reversal is not sufficiently high for oxidation and, consequently, deposition does not occur at this step of the process.

This process of glass layer deposition repeats itself for a designed number of times (typically, the order of 100 layers are deposited) until the flow of chlorides is finally interrupted. At this stage, the preform still has a void in its center. To close this void the temperature of the tube is increased and due to surface tension effects the whole structure collapses gradually with the passage of the torch. The end result is a composite rod consisting of an outer cladding originated from the substrate tube itself surrounding an inner core of concentrically deposited glass layers.

To manufacture a certain type of optical fiber, multimode, monomode, or any of its variations, a specific recipe has to be designed, basically defining the relative flows of chlorides step by step during the deposition process. As shown in figure 16, the refractive index profile of the optical fiber will be determined by the composition of the glass layers constituting the core of the preform.

2.2.2 Outside vapour deposition

This process of preform manufacturing , called by the same name as indicated above , Outside Vapour Deposition (OVD), has a basic set-up consisting of 2 parts. As shown in figure 17, the first part combines a gas flow control unit, a support mechanism for a rotating rod and an exhaust system. With this first set-up, porous preforms are manufactured to be subsequently sinterized in a separate set-up consisting of a furnace with controlled atmosphere.

The combined flow of chlorides coming from the gas control unit is fed into a motorized torch which traverses back and forth parallel to a substrate rod. The rod rotates in a supporting mechanism similar to a lathe. When the chlorides exit from the torch, a flame hydrolysis reaction occurs generating fine soot particles of oxide glasses. Following the direction of the flame the particles are directed towards the bait rod and are collected there. This process repeats itself while the porous preform being manufactured grows radially out, as shown in figure 18.

When the proper size is obtained the inner rod is removed, leaving the preform with a void in its center. At this stage the preform is a bulky whitish cylinder with a porous structure, but already has all the basic characteristics of the optical fiber to be pulled from it except, again, the absolute geometrical dimensions.

The next step of the OVD process consists of sinterizing the porous structure of the preform. This step, also called consolidation, is carried on a vertical furnace where, similarly to a zone refining process, the glass particles are vitrified collapsing around the center void. During this consolidation step the atmosphere inside the furnace is controlled to remove contaminants and also to avoid the entrapment of air bubbles inside the structure of the preform.

The final product of the OVD process is a preform completely manufactured by the deposition of glass particles obtained from the oxidation of chlorides. Differently than MCVD, in this case the outer cladding is also manufactured during the process.

In a similar way as in the MCVD process, as shown in figure 16, the profiling of the refractive index is done by controlling the flux of chlorides and consequently the composition of the deposited layers. The basic difference is that the recipe has to be inverted to follow the inside-out deposition order.

2.2.3 Variations of the vapour deposition process

Both MCVD and OVD have been studied in search for more efficient and more economical processes. The 2 most promising variations which have resulted in commercial production so far are called Vapour Axial Deposition (VAD) and Plasma Enhanced Chemical Vapour Deposition (PEMCVD).

The VAD process is a variation of OVD with the basic difference that the soot particles are deposited in the axial direction from an initial bait, as shown in figure 19. In this case the entire cross section of the preform is deposited simultaneously. The profiling of the refractive index is determined by the selective trajectory of soot particles leaving the deposition torch. This process of deposition also permits the simultaneous consolidation of the porous preform, eliminating therefore an extra step in the manufacturing process.

The PEMCVD process is very similar to MCVD with the exception that the oxidation reaction is enhanced by the existence of a plasma reactor. Actually as the name" Modified" in MCVD indicates this process itself is in a way a variation of a more basic process called Chemical Vapour Deposition (CVD).

In basic CVD, one of the first processes used in R&D but never on a commercial production scale, the oxidation of chlorides occurred only next to the inner walls of the substrate tubes. These are so called heterogeneous reactions since 2 phases are present in the reaction (solid and gas). Without any modification this was unfortunately a very slow deposition process. MCVD did a subtle but very efficient modification to the CVD process by increasing the flow of chlorides. This way also homogeneous (gas only) reactions were allowed to occur inside the substrate tubes, away from the inner walls. The end result was a faster and therefore more economical production process.

The creation of a plasma in the reaction zone, enhances the oxidation of the chlorides to an extent that the homogeneous reaction becomes even more efficient from the production point of view. The plasma is created by the radiation generated from an RF coil. By PEMCVD, as shown in figure 20, very thin layers are deposited on the substrate tube but with a much faster speed as compared to MCVD. Aside from a potentially better control on the refractive index, PECVD also allows for a more economical process regarding the cost of raw materials since the chlorides are completely oxidized inside the substrate tube.

2.3 Fiber pulling

This is the last step in the manufacturing of an optical fiber. Ideally,the pulling process should accomplish only two main objectives, which in principle seem rather simple: define the final outside diameter of the fiber and protect its outer surface by the application of a coating. In practice, however, some complications may arise if proper quality control measures are not taken.

2.3.1 Pulling tower

As shown in figure 21, fiber pulling is accomplished in a tower specifically constructed for that purpose. The preforms are held vertically on the upper part of the tower and are slowly fed into a high temperature (~2000°C) furnace. The pulling process is started by allowing the bottom end of the preform to fall down freely with gravity from underneath the furnace. Inside the furnace the preform is heated up developing a draw-down region. That takes the final diameter of the preform to that of a hair thin fiber. The fiber is then passed through a motorized pulley which from then on pulls down the fiber directing it to a winding drum. Before the fiber reaches the pulley, it is coated for mechanical protection.

2.3.2 Draw-down region

The basic objective of the pulling process is to change the geometrical dimensions of the preform to that of a fiber with an outside diameter standardized to 125 microns. Considering a typical preform diameter of 30 mm, the reduction factor to be accomplished is of the order of 300:1. This rather sharp geometrical transformation has to occur inside the furnace in a short region of a few centimeters where the preform is in a liquid state. As shown in figure 22, as soon as the fiber leaves the hot zone, still inside the furnace, the material goes through its glass transition and the geometry is frozen. The cylindrical symmetry necessary in the optical fiber is greatly facilitated by the strong surface tensions effects in the material due to its small radius. But it is fundamental that the furnace generates a symmetrical heating zone with the highest possible degree of stability. Any deviations in temperature or symmetry in this heating zone will cause variations in the diameter or circularity of the fiber, due to geometrical changes in the profile of the draw-down region.

The accepted deviation in the outer diameter of the optical fiber is +- 3 microns. Since the diameter of the preform also necessarily vary along its length, the pulling speed of the fiber has to compensate for this variation in such a way as to keep the final diameter of the fiber constant. This is accomplished by a closed loop set-up in the pulling tower consisting of a diameter measuring device coupled to the motorized pulley that pulls down the fiber. The diameter measuring apparatus, as shown in figure 23, is a non-contact device that essentially measures the shadow left by the fiber in a photo-detector.

2.3.3 Heating furnace

The transmission parameters of the optical fiber are actually defined in the preform manufacturing step. So, as long as the final diameter of the fiber is maintained within the specified tolerance, fiber pulling does not change, for better or worse, the optical characteristics of the fiber.

But the opposite is true regarding the mechanical strength of the optical fiber. This is essentially determined by the pulling process as long as no gross defects are present in the preform.

As mentioned before, in order to preserve the intrinsic high strength of a glass fiber it is necessary to protect its surface maintaining it as free of defects as possible. When the fiber is first formed, still in the draw-down region inside the furnace, its outer surface is in the ideal state. But it is almost impossible to avoid the contamination of this surface before the fiber is finally coated in the pulling tower. The main sources of contamination arise from the furnace itself.

Any particle liberated from inside the furnace has a strong probability of ending up adhering to the soft surface of the fiber, creating this way a localized defect which might give rise to a mechanical failure later on. As shown in figure 24, two types of furnaces have been used so far for pulling optical fibers: resistance and induction furnaces. The first type uses graphite resistance elements through which are passed very high electrical currents. In order to preserve the burning of these elements, an inert atmosphere usually consisting of O_2 free N_2 gas has to be maintained next to the elements. Induction furnaces use zirconia elements which heat up to the desired temperature when subjected to an alternating electromagnetic field generated by an RF coil. Since the zirconia element is not susceptible at room temperature, graphite elements are used to heat up the furnace, being subsequently removed. Even though considerable improvements have been made in the performance of these furnaces, they still are not 100% free of contaminants. Lately, induction furnaces have become more common in production in spite of its larger cost as compared to graphite furnaces.

2.3.4 Fiber coating

As soon as the fiber is cooled down along the pulling tower it is then coated to preserve its surface from abrasion. The materials most commonly used today for fiber coating are acrylate polymers. Aside from showing excellent adherence to the fiber surface these materials have the added advantage of being cured by ultraviolet radiation. This allows a fast and homogeneous polymerization of the coating . As shown in figure 25, the coating is applied to the fiber by passing it through a die containing the acrylate in liquid form. The coated fiber is then passed inside a curing oven where the acrylate is polymerized leaving then a hard film adhered to the surface of the fiber. Typically, the final diameter of the coated fiber is 250 microns.

An alternative coating material is silicone. The application to the fiber is done basically in the same way with the exception that in this case the polymerization occurs by thermal conduction through the thickness of the silicone film. Instead of an ultraviolet oven , a conventional resistance oven is now used. Silicone coatings have the advantage of acting as a soft mechanical buffer protecting the fiber from radial mechanical stresses. Also, a silicone coating is easily removed during splicing operations.

On the other hand, acrylate coatings allow for a much more homogeneous mechanical strength along the whole length of the fiber. An added advantage of acrylate coatings is that the pulling speed can be greatly increased as compared to silicone coatings ,due to the type of curing of these two polymers.

To guarantee a minimum mechanical performance, optical fibers are proof-tested in factory by passing their whole length through a fixed load. Typically, proof-test values of 50 KPSI are being practiced.

2.4 Optical fiber cable

The use of an optical fiber in a commercial telecommunication link requires necessarily that the fiber be properly packaged in the form of a cable. Since the environment existent in the usual routes for these links show very adverse conditions, cables are needed to protect the fibers the same way as in the case of copper wires or coaxial waveguides.

The technology for optical fiber cabling is very similar to conventional cabling and therefore will not be explored in much detail. Only considerations regarding the basic differences will be analyzed.

2.4.1 Cable units

Two types of packaging for individual fibers have been practiced so far by the cabling industry. These constitute the basic units which are then cabled in much the same way as other cables. These types of packaging have been called "loose" and "tight" fittings. In the first case ,as shown in figure 26, hard polymer tubing are extruded while acrylate coated fibers are "loosely" fed inside of them. The identification of individual fibers is allowed by a

color coding procedure which is applied to the coatings at a previous step in the manufacturing process. Typically , up to 6 pairs of fibers are packaged this way.
An alternative type of packaging, usually applied to silicone coated fibers, consists of extruding a "tight" coating of a polymer such as Nylon, around an individual fiber. In this case the color coding is applied to the outer coating .

2.4.2 Microbending

The main problem regarding the cabling of optical fibers relates to the possibility of increasing the attenuation of the fibers. The mechanism for this effect is called microbending. As the name indicates this phenomenon occurs whenever the fiber is forced to microcurvatures inside its packaging, as shown in figure 27. At the point where these microcurvatures occur, the propagation of radiation is severely affected in the fiber with the end result of an excessive optical loss accumulated along the length of the fiber.

Usually this effect is a consequence of a mismatch in the thermal behavior of the materials used in the packaging operation. After cooling from extrusion, the different contraction of the materials forces the fiber towards the inner walls of its immediate surroundings ,giving rise to microbendings.

A poor cable design can also allow for microbending effects if the fiber is not given sufficient room inside the cable to move when the cable is bent or stretched. This is a parameter carefully controlled in loose-fittings by allowing an extra length of fiber in relation to the outer tubing.

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FIGURE 1

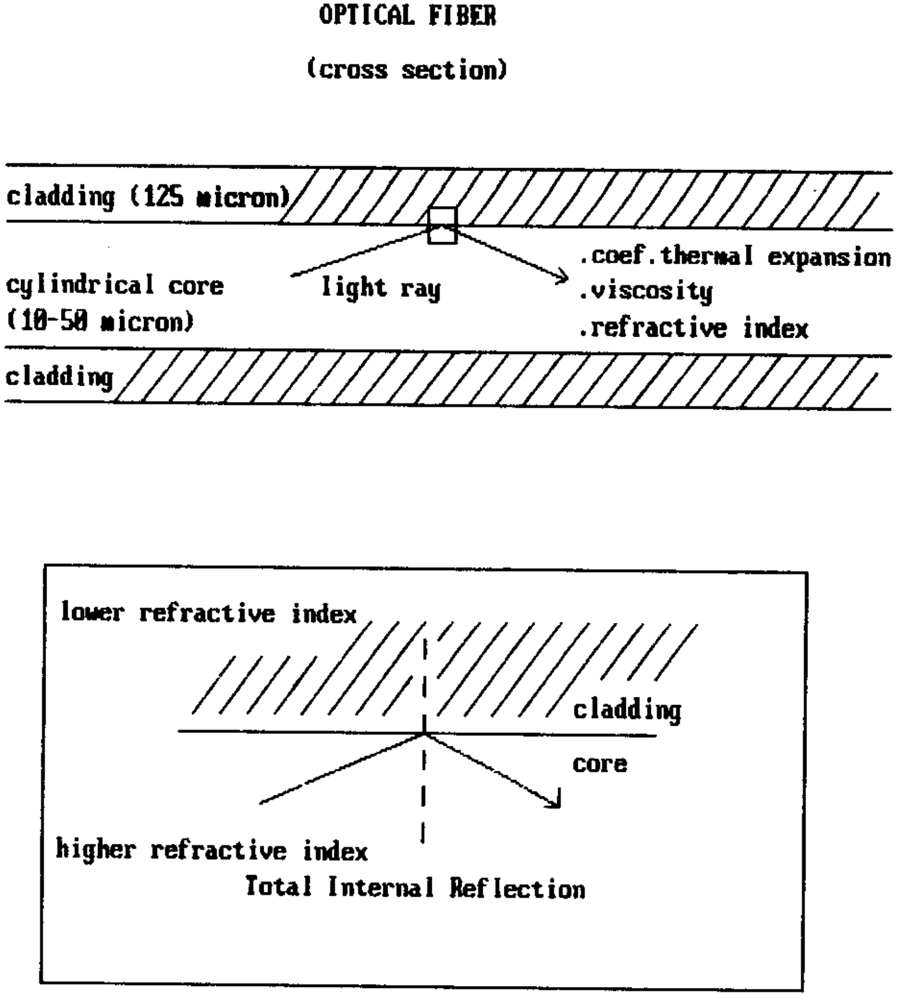


FIGURE 2

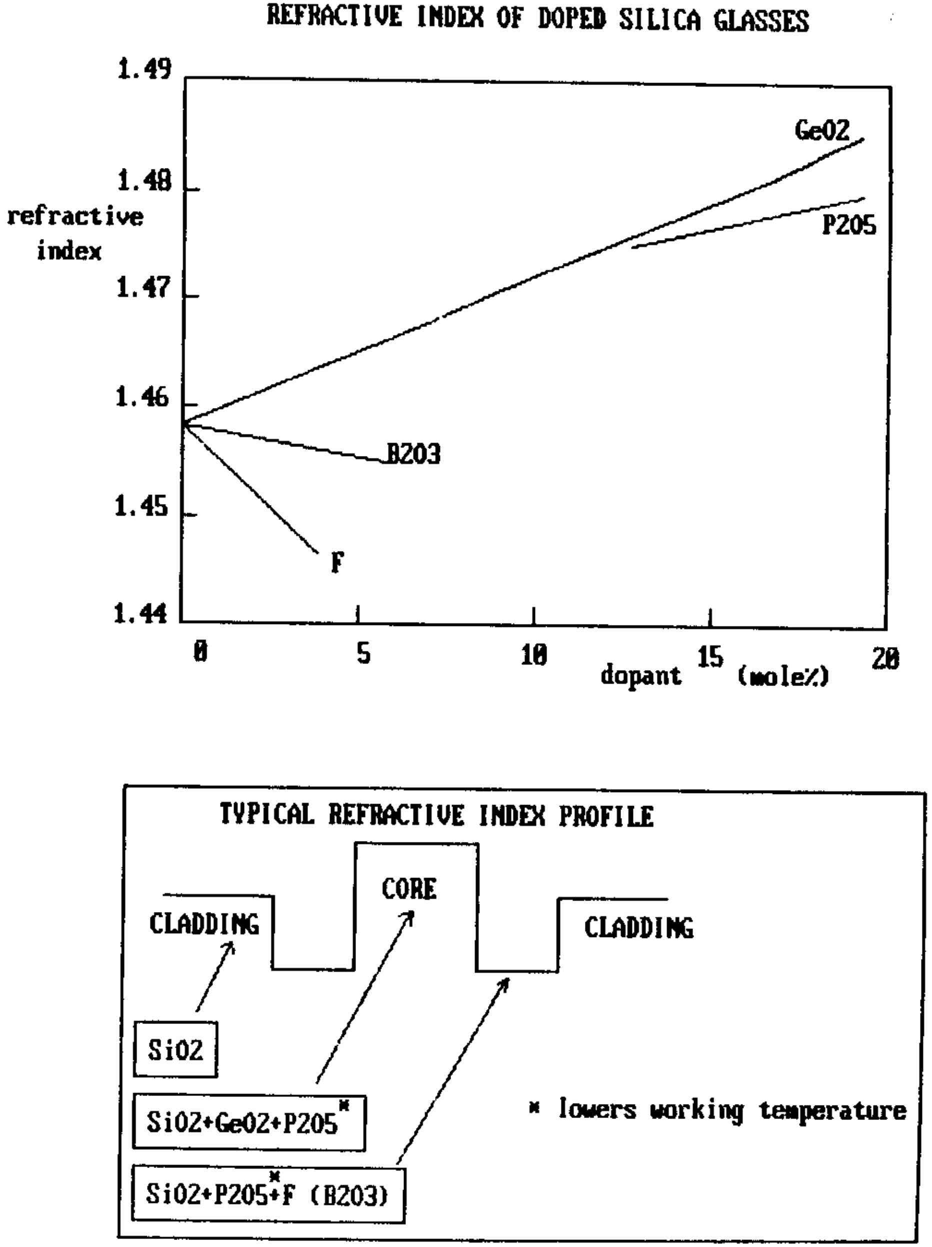
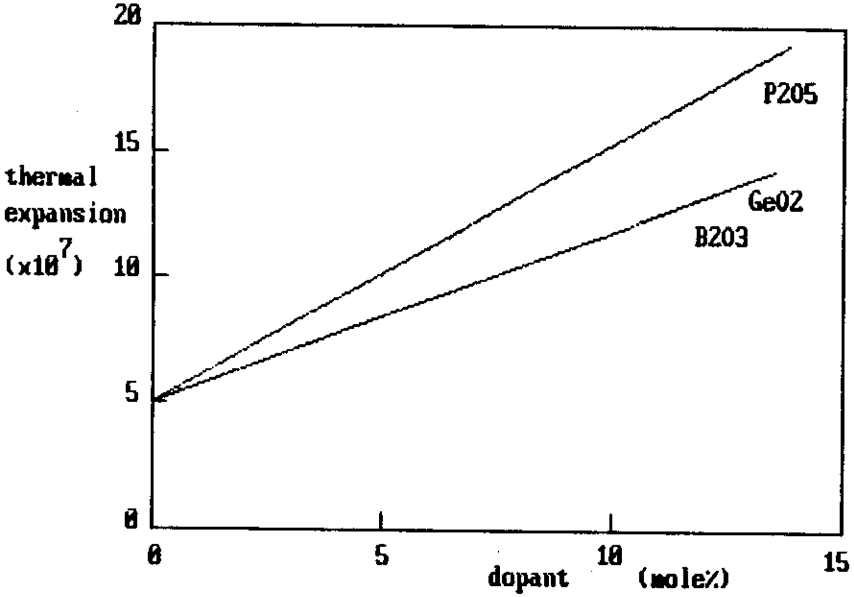


FIGURE 3

THERMAL EXPANSION OF DOPED SILICA GLASSES



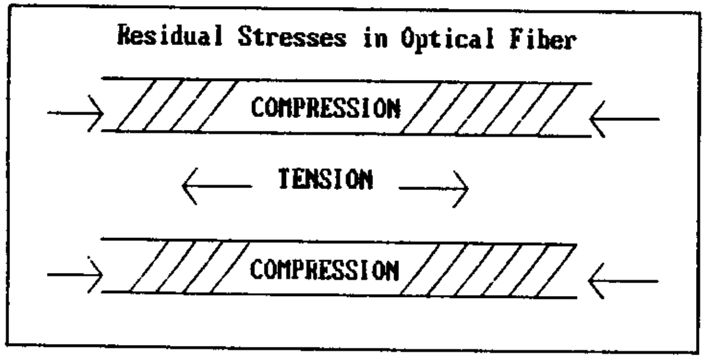


FIGURE 4

OH OVERTONES AND COMBINATIONAL VIBRATIONS IN VITREOUS SILICA

WAVELENGTH (micrometers)	FREQUENCY	LOSS* (dB/km)
0.82	2f1+3f3	4
0.88	f1+3f3	90
0.945	3f3	1,000
1.13	2f1+2f3	110
1.24	f1+2f3	2,800
1.38	2f3	65,000
1.9	2f1+f3	10,300
2.22	f1+f3	260,000
2.72	f3	10,000,000

f1.....BENDING MOTION

f3.....STRETCHING VIBRATION

(* for an OH^- concentration of 1200 ppm)

FIGURE 5

ABSORPTION LOSS FROM TRANSITION METAL IONS

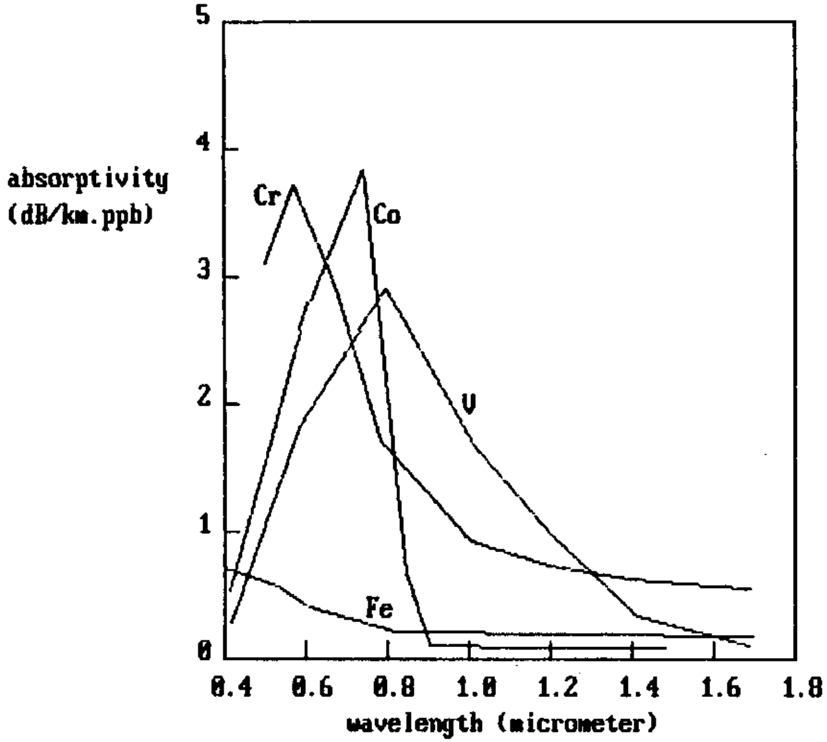


FIGURE 6

ABSORPTION AND SCATTERING LOSSES

Germania doped silica fiber

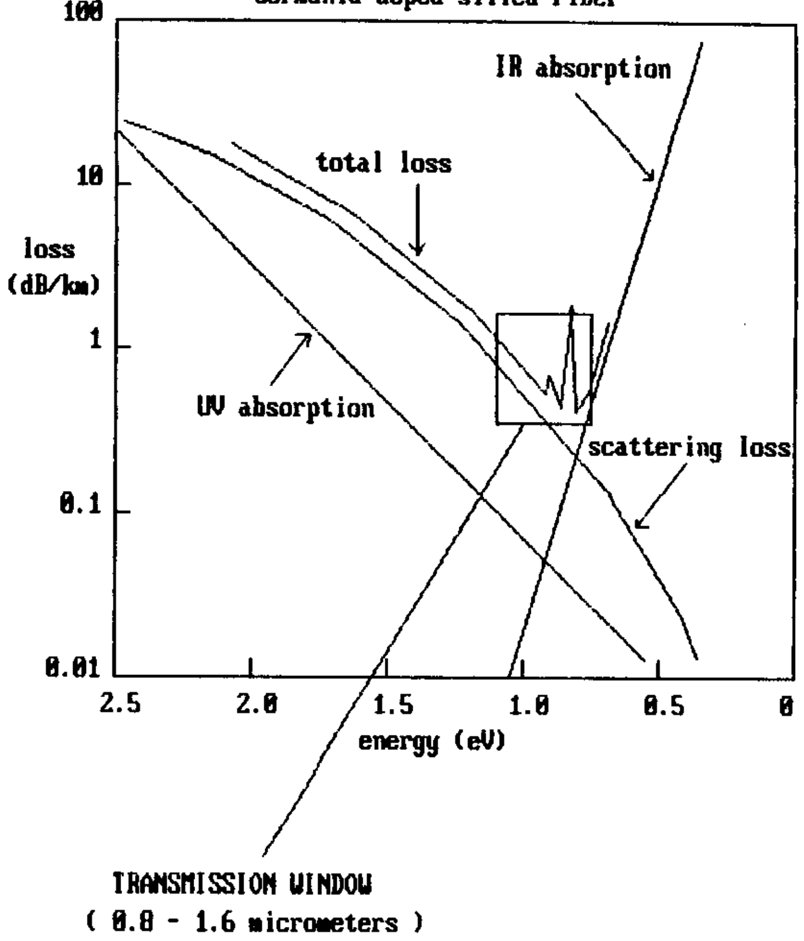
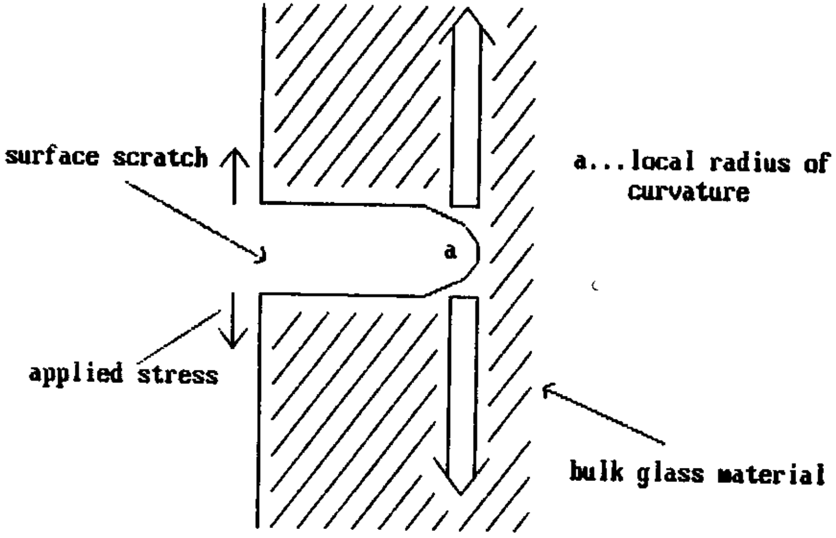


FIGURE 7

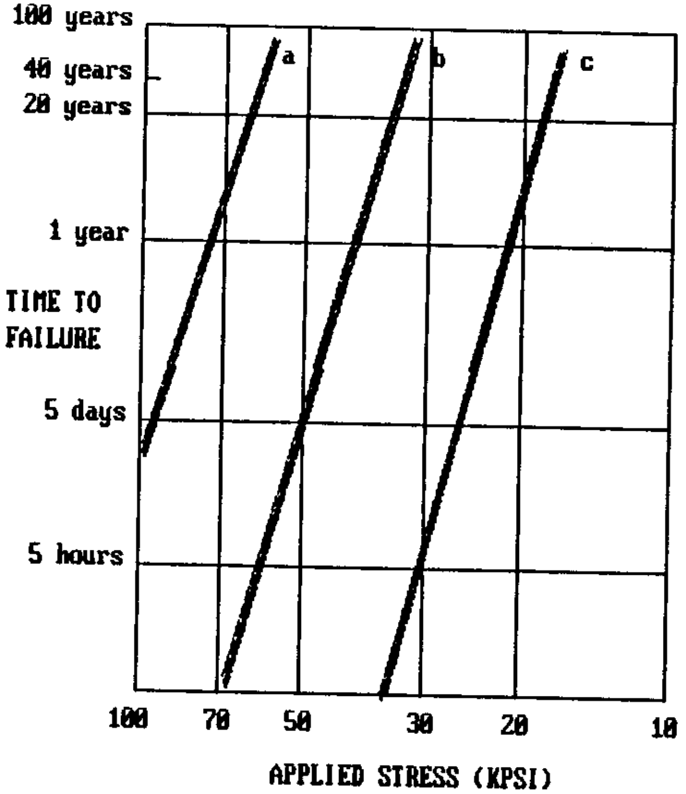
MECHANICAL FAILURE OF GLASS FIBERS



Local stress proportional to $(a)^{-\frac{1}{2}}$

FIGURE 8

STATIC FATIGUE



	PROOF TEST LEVELS
a	200 KPSI
b	100 KPSI
c	50 KPSI

FIGURE 9

SILICATE GLASS MANUFACTURING

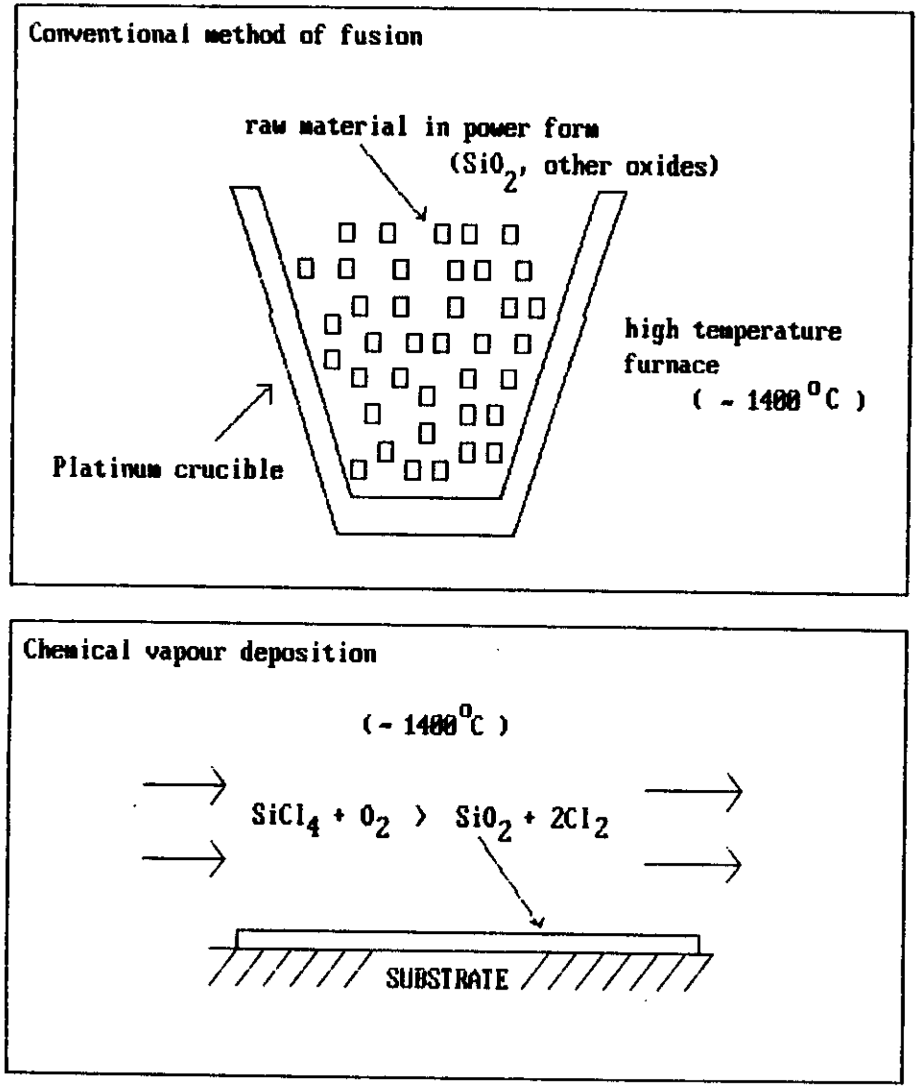
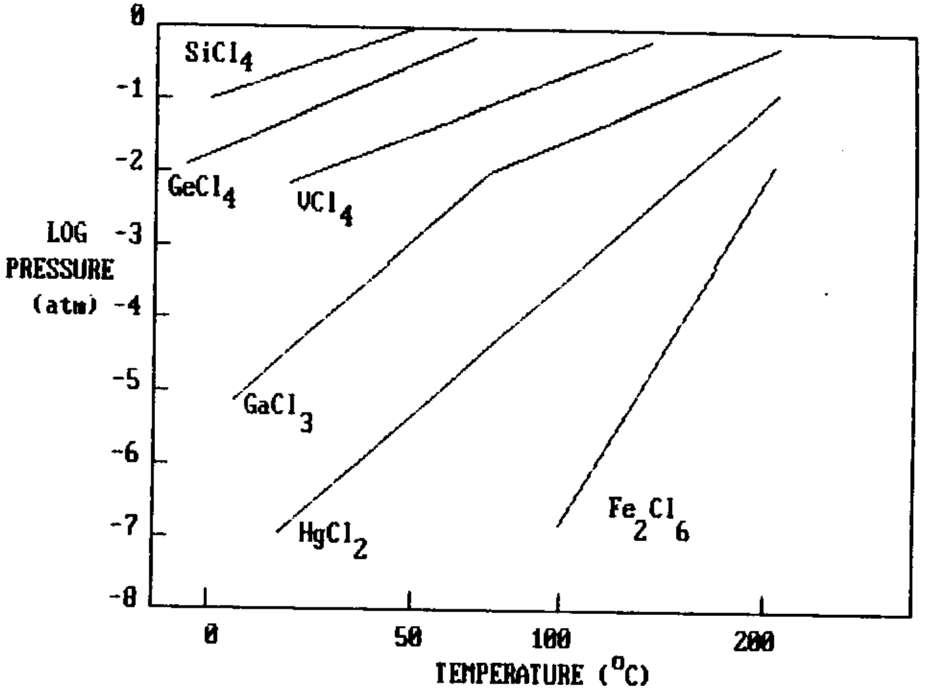


FIGURE 10

VAPOUR PRESSURE OF CHLORIDES



Silicon and Germanium chlorides have high vapour pressures in comparison to other metal halides.

FIGURE 11

OPTICAL FIBER FABRICATION

2 STEP PROCESS

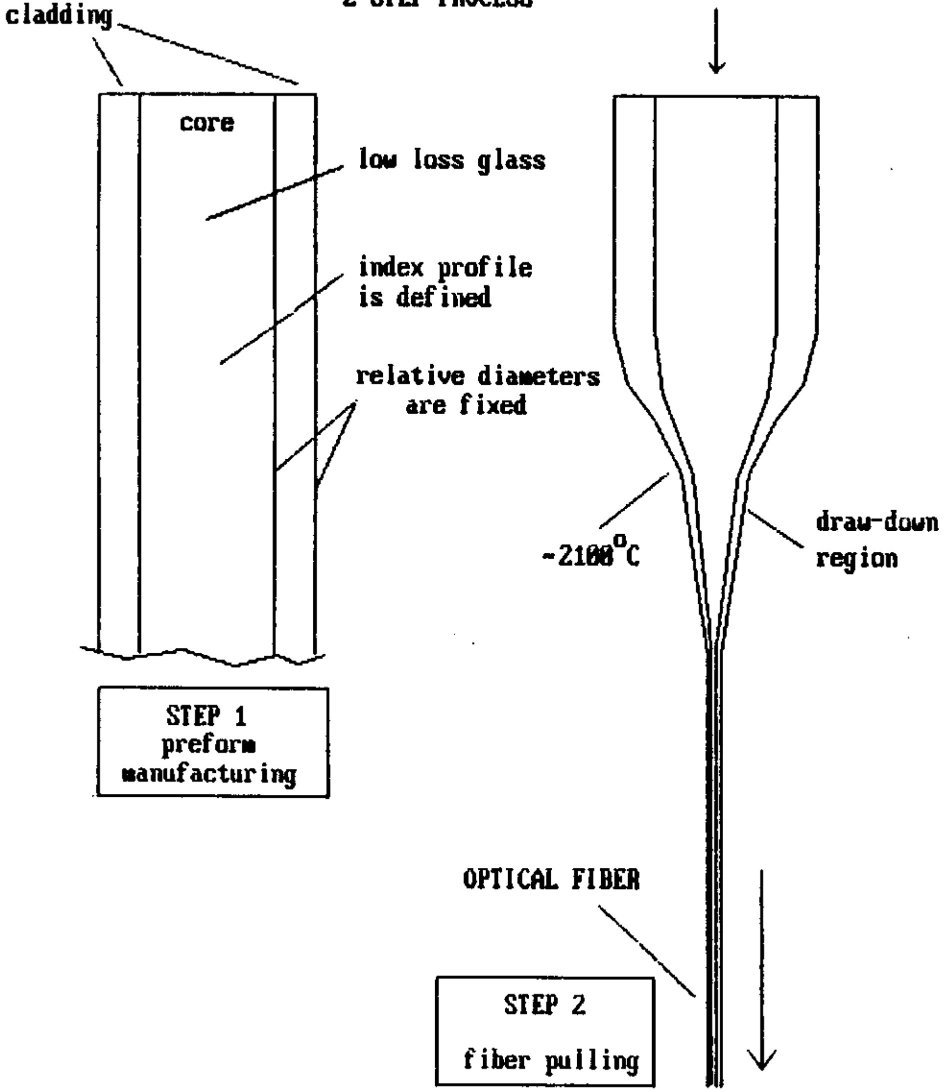
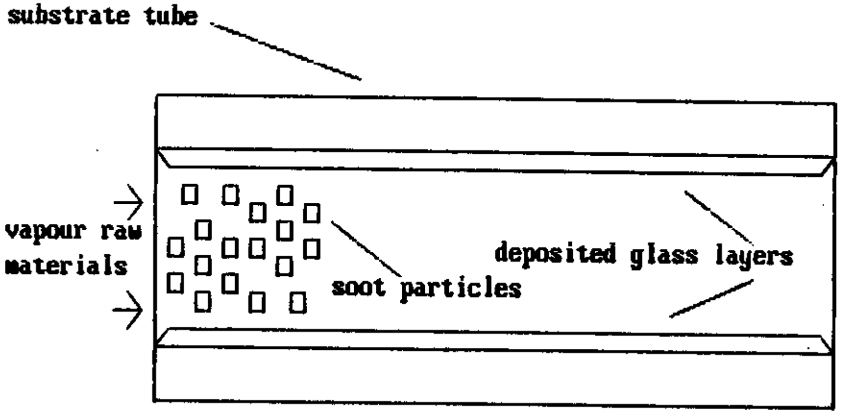
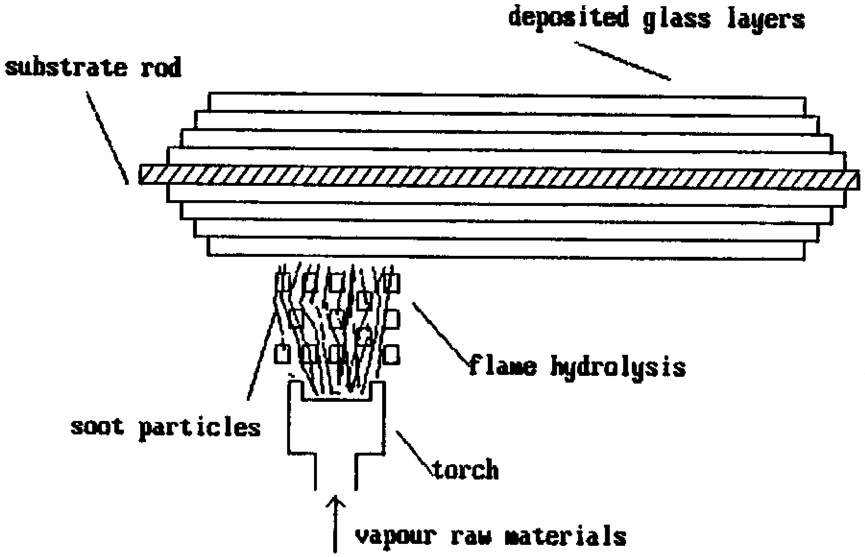


FIGURE 1

PREFORM MANUFACTURING PROCESS



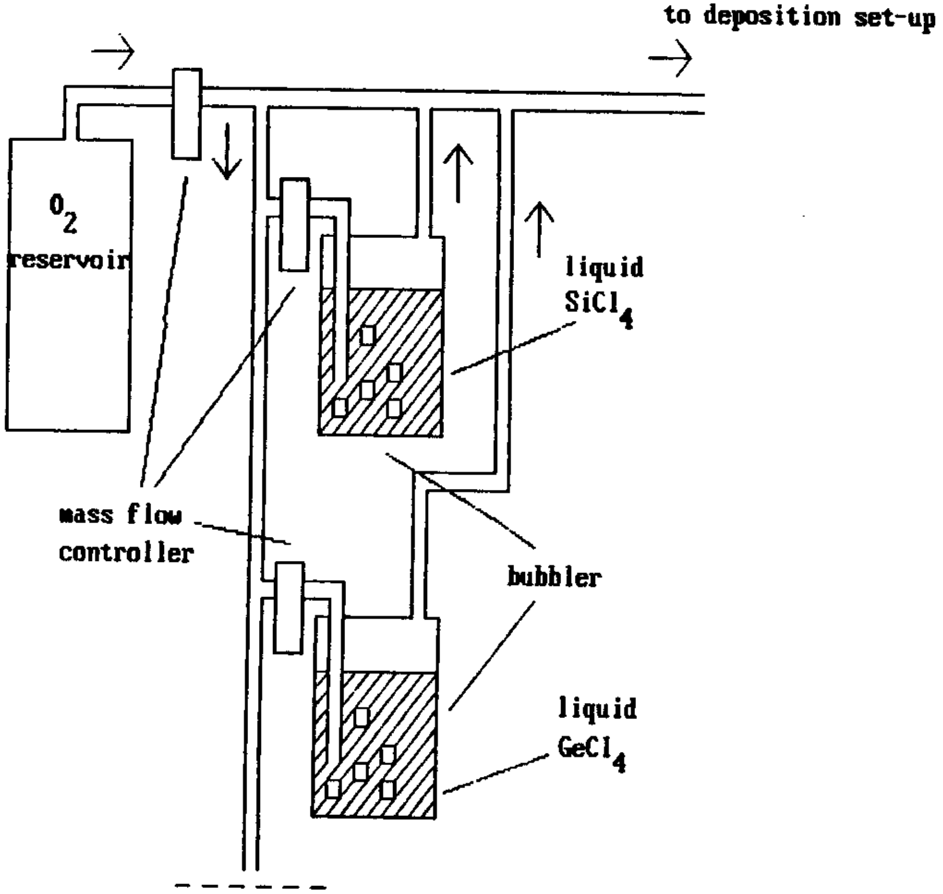
INSIDE VAPOUR DEPOSITION



OUTSIDE VAPOUR DEPOSITION

FIGURE 13

FLOW CONTROL SET-UP



OXYDATION REACTIONS

$SiCl_4 + O_2 > SiO_2 + 2Cl_2$

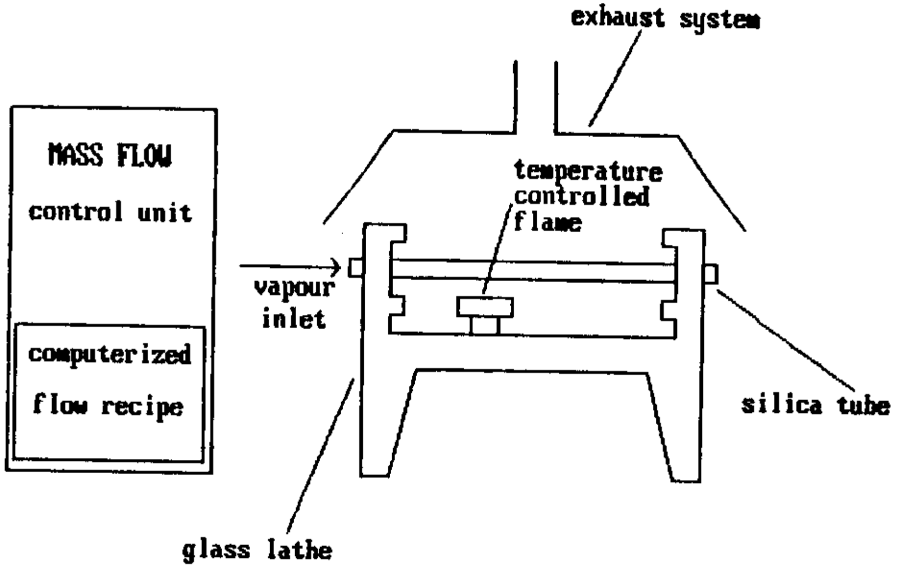
$GeCl_4 + O_2 > GeO_2 + 2Cl_2$

$4POCl_3 + 3O_2 > 2P_2O_5 + 6Cl_2$

$4BCl_3 + 3O_2 > 2B_2O_3 + 6Cl_2$

FIGURE 14

INSIDE VAPOUR DEPOSITION

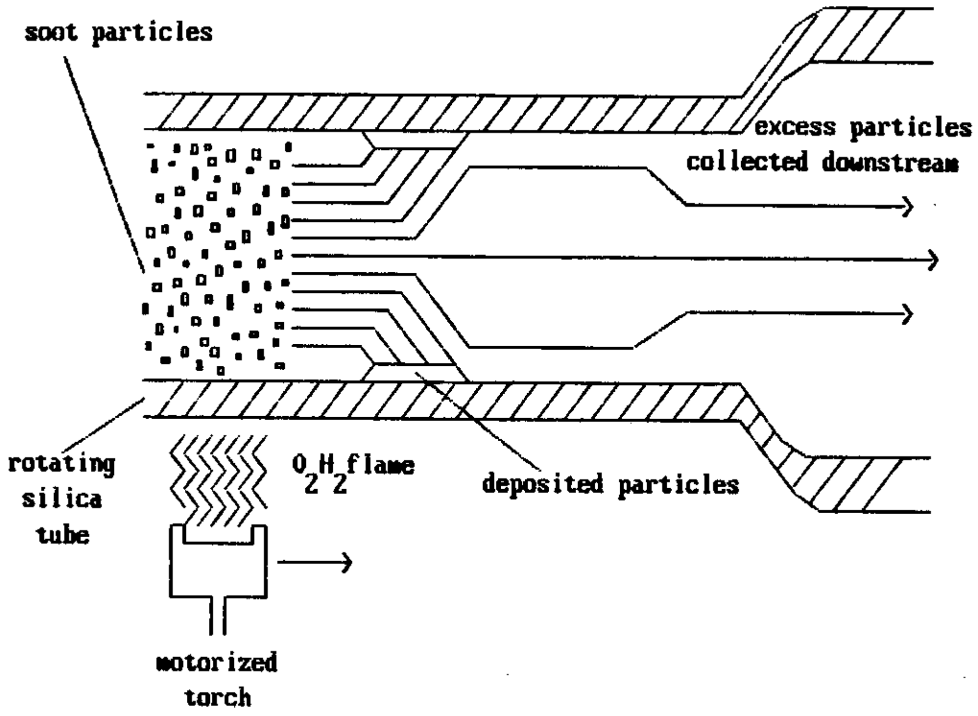


downstream direction......DEPOSITION
oxydation and vitrification

upstream direction........RETURN
change in flow
at control unit

FIGURE 15

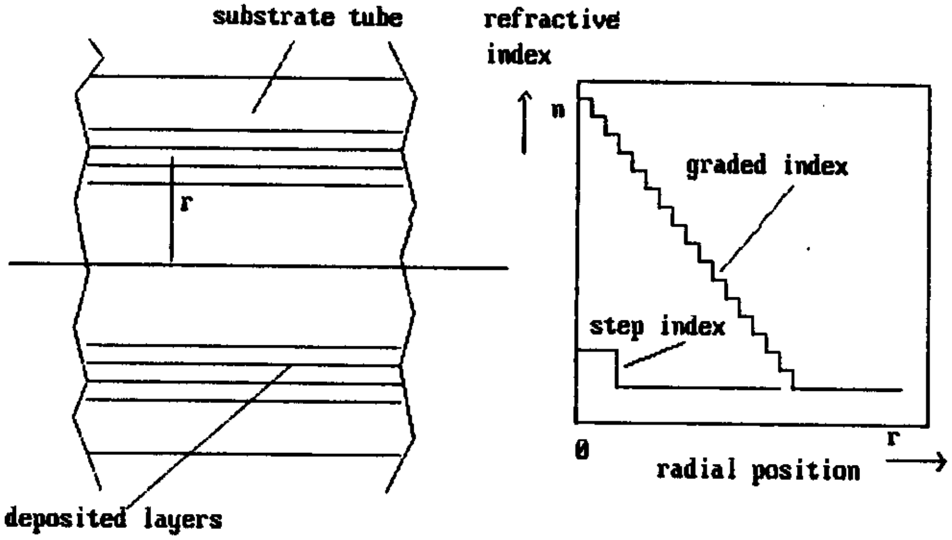
GLASS DEPOSITION BY MCVD



- TRAJECTORIES OF PARTICLES DEFINED BY THERMOFORESIS
- DEPOSITED PARTICLES ARE SINTERIZED AFTER PASSAGE OF TORCH
- COMPOSITE TUBE COLLAPSES BY INCREASING THE TEMPERATURE

FIGURE 16

INDEX PROFILING

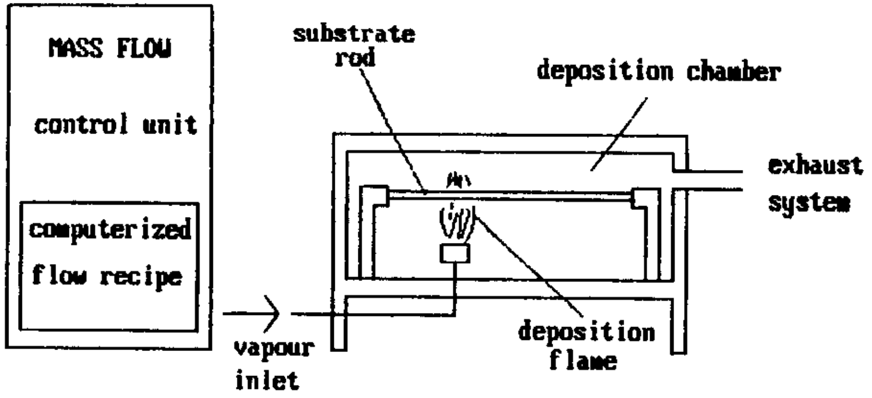


- REFRACTIVE INDEX OF EACH LAYER DETERMINED BY RELATIVE CONCENTRATION OF SiO_2 AND DOPANTS
- RELATIVE RADIAL COORDINATES ARE CHANGED DURING COLLAPSE OF PREFORM (cross sectional area of each layer is maintained)

FIGURE 17

OUTSIDE VAPOUR DEPOSITION SET-UP

1 - POROUS PREFORM MANUFACTURING



2 - SINTERIZATION OF PREFORM

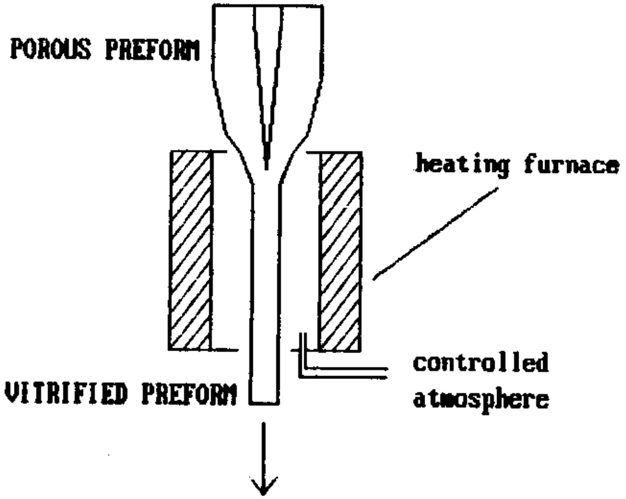


FIGURE 18

OVD POROUS PREFORM

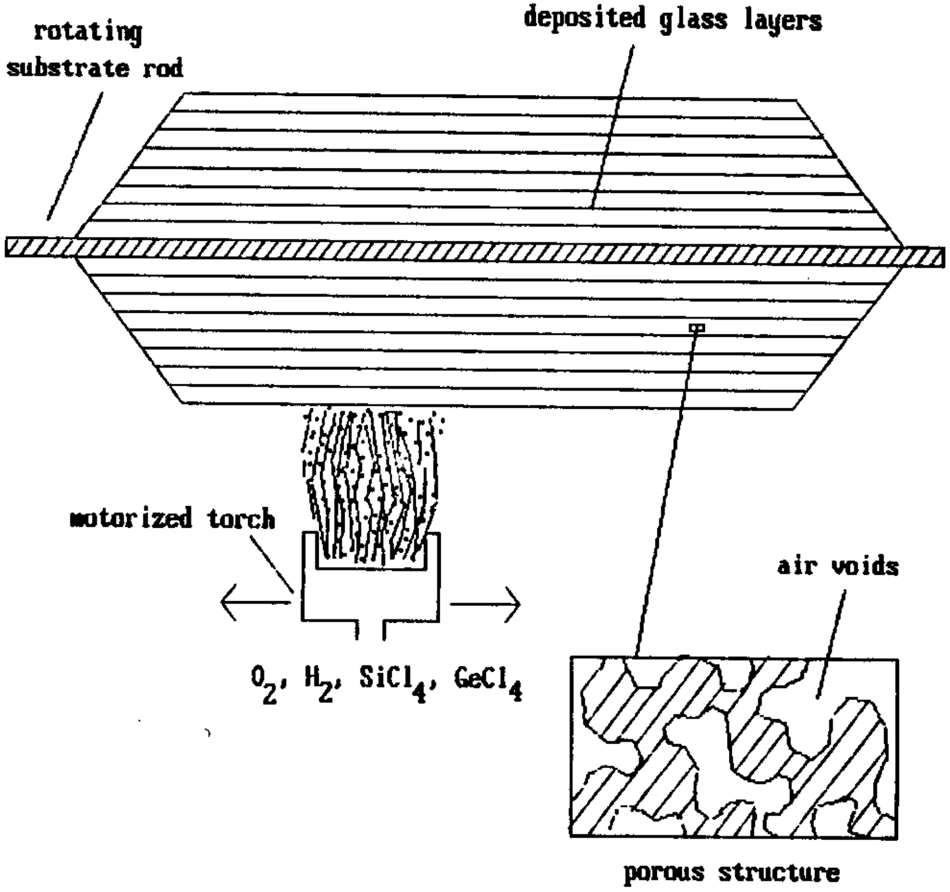


FIGURE 19

VAPOUR AXIAL DEPOSITION
(VAD)

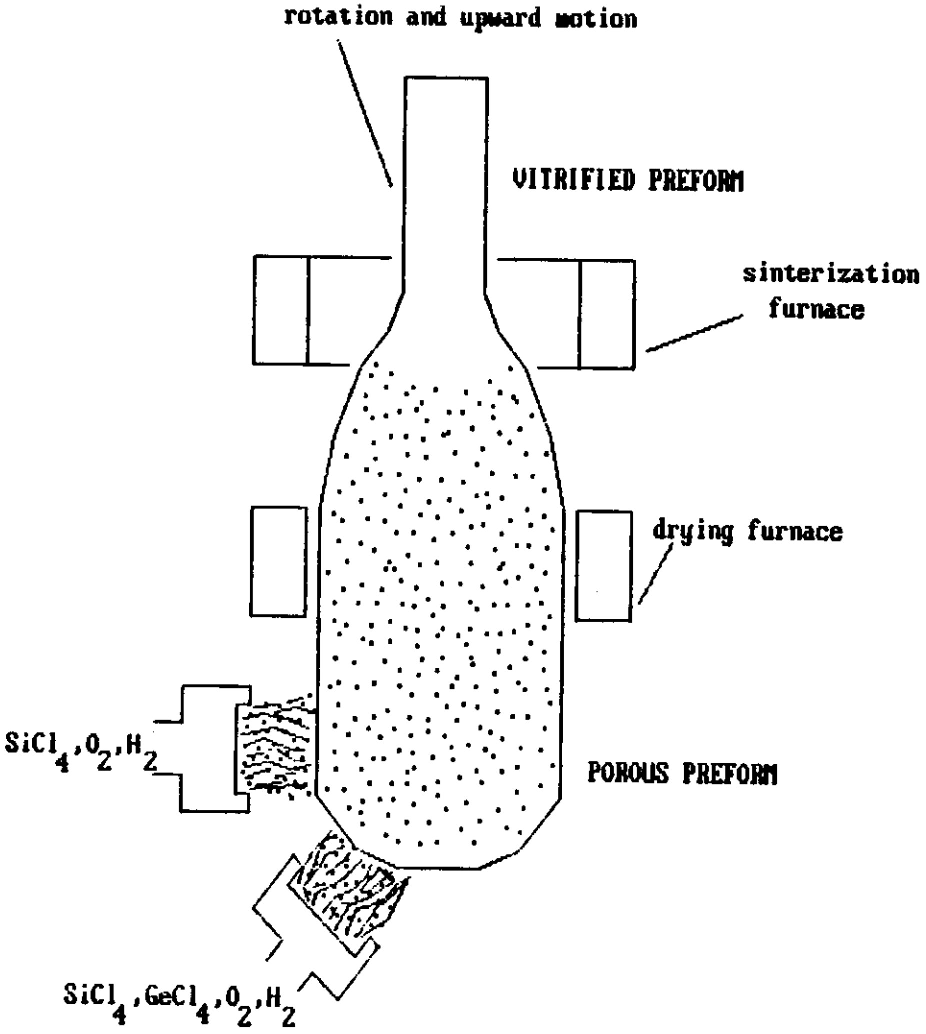
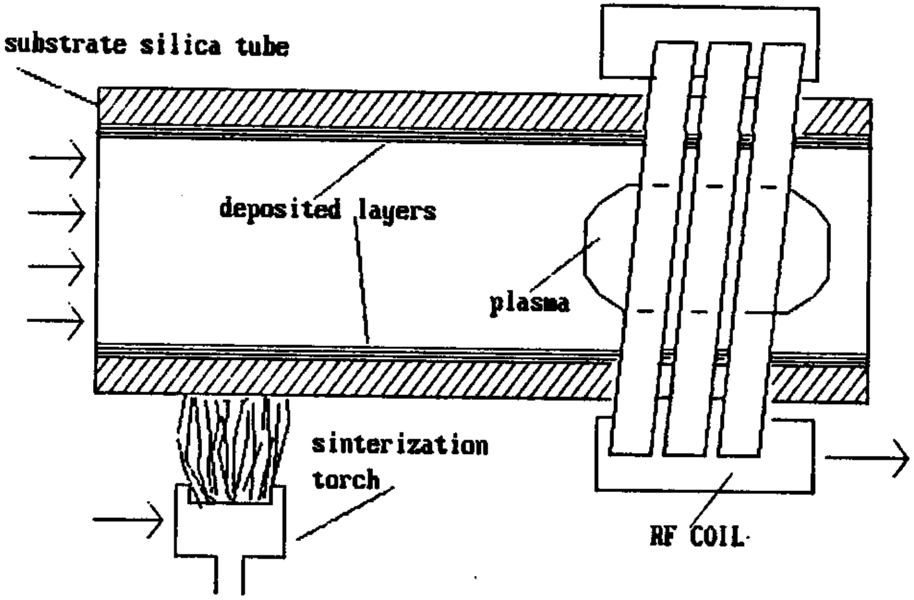


FIGURE 20

PLASMA ENHANCED CHEMICAL VAPOUR DEPOSITION
(PECVD)



- OXYDATION OF CHLORIDES ENHANCED BY PLASMA
- INDEPENDENT MOTION OF TORCH AND RF COIL

FIGURE 21

FIBER PULLING TOWER

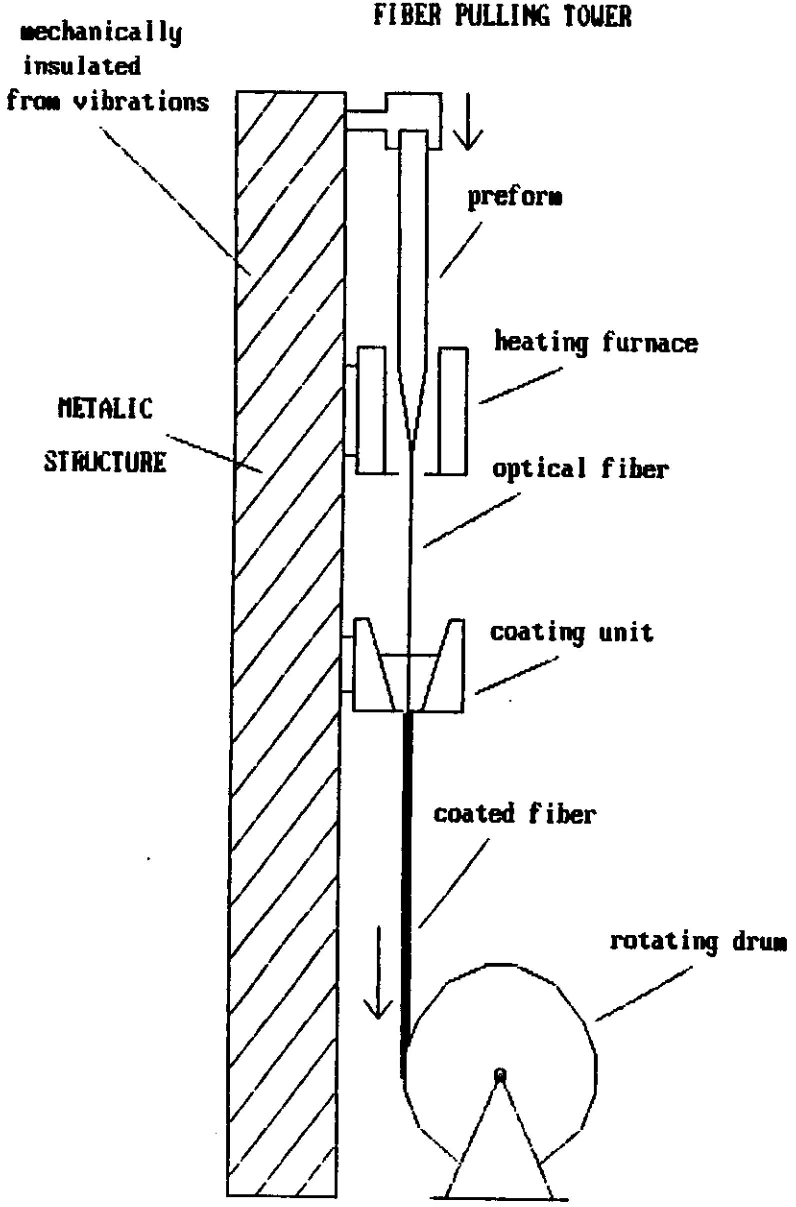
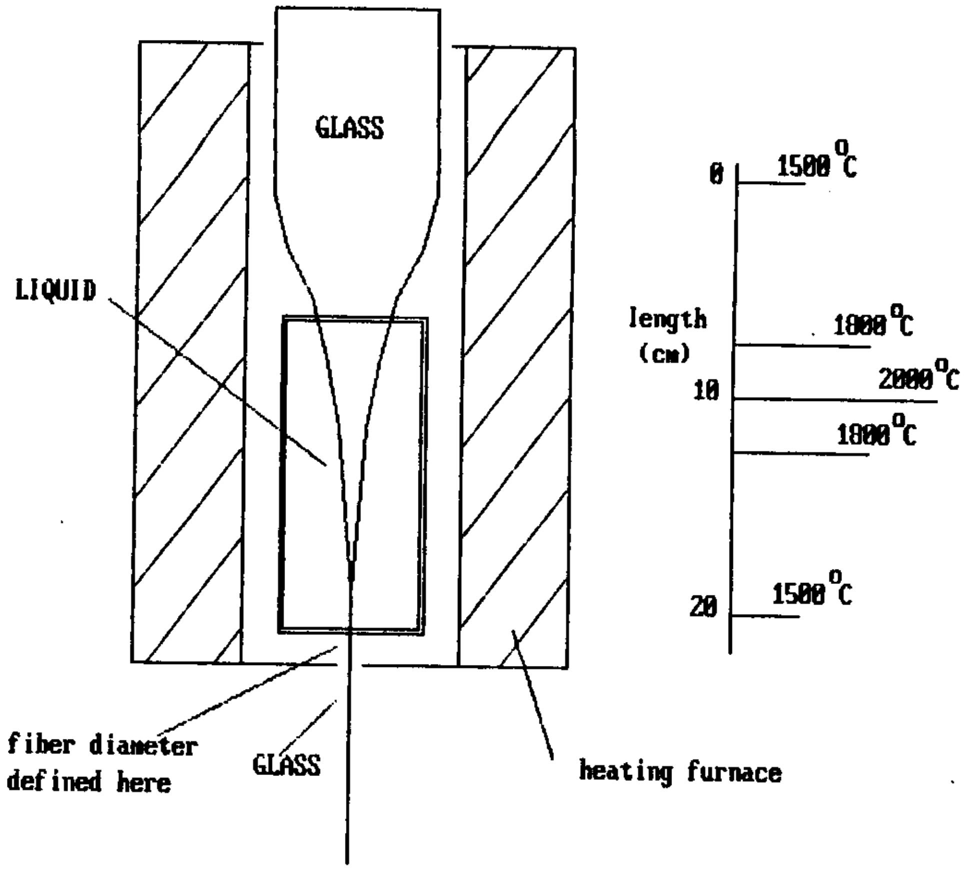


FIGURE 22

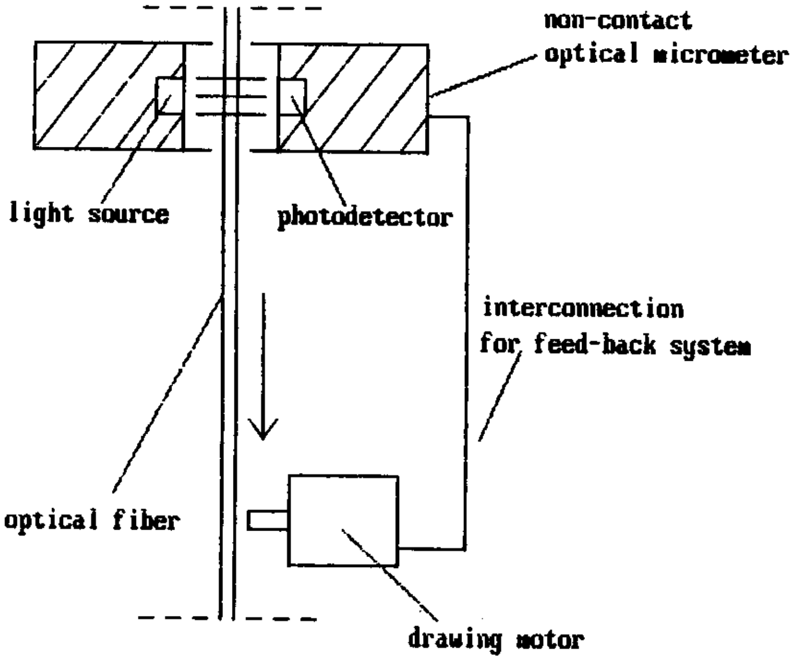
DRAW-DOWN REGION



- AFTER GLASS TRANSITION, GEOMETRY IS FROZEN
- GEOMETRICAL PRECISION DEPENDS ON CYLINDRICAL SYMMETRY AND STABILITY OF HOT ZONE

FIGURE 23

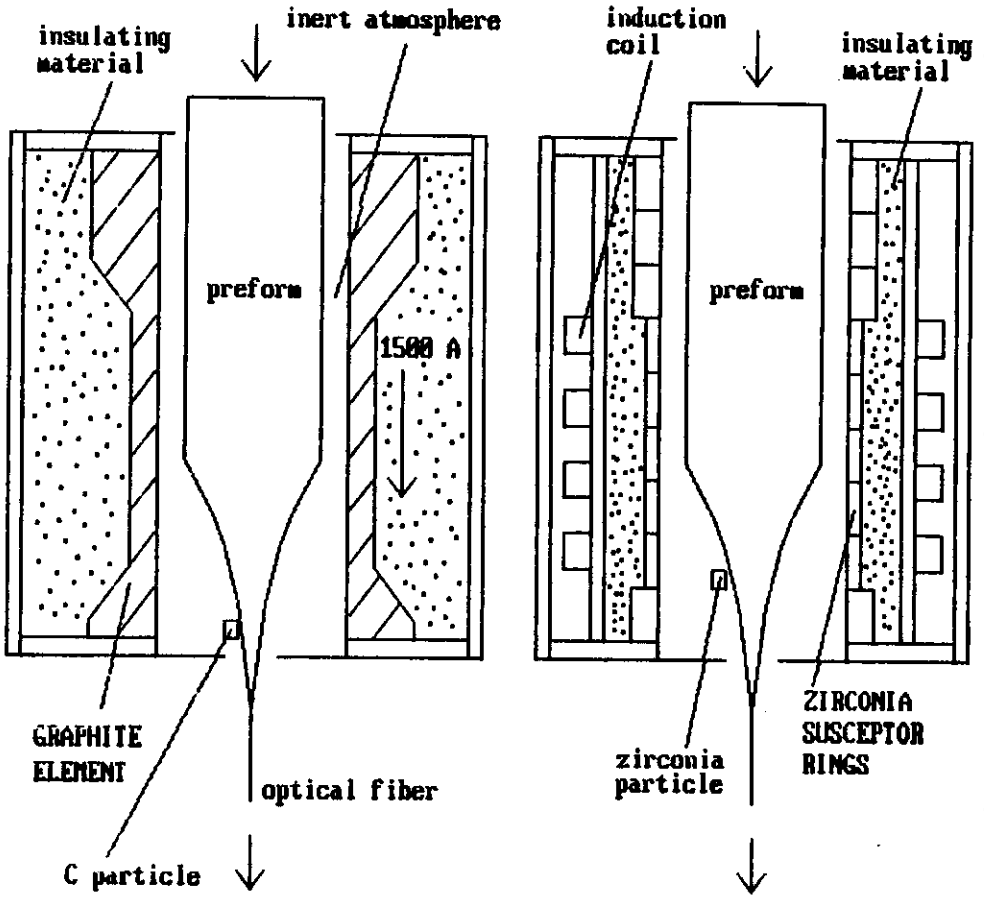
DIAMETER CONTROL



- OUTSIDE DIAMETER 125 micrometers
- STANDARDIZED TOLERANCE +- 3 micrometers
- PULLING SPEED -3 m/sec

FIGURE 24

HEATING FURNACES FOR PULLING OPTICAL FIBERS



RESISTANCE FURNACE

INDUCTION FURNACE

FIGURE 25

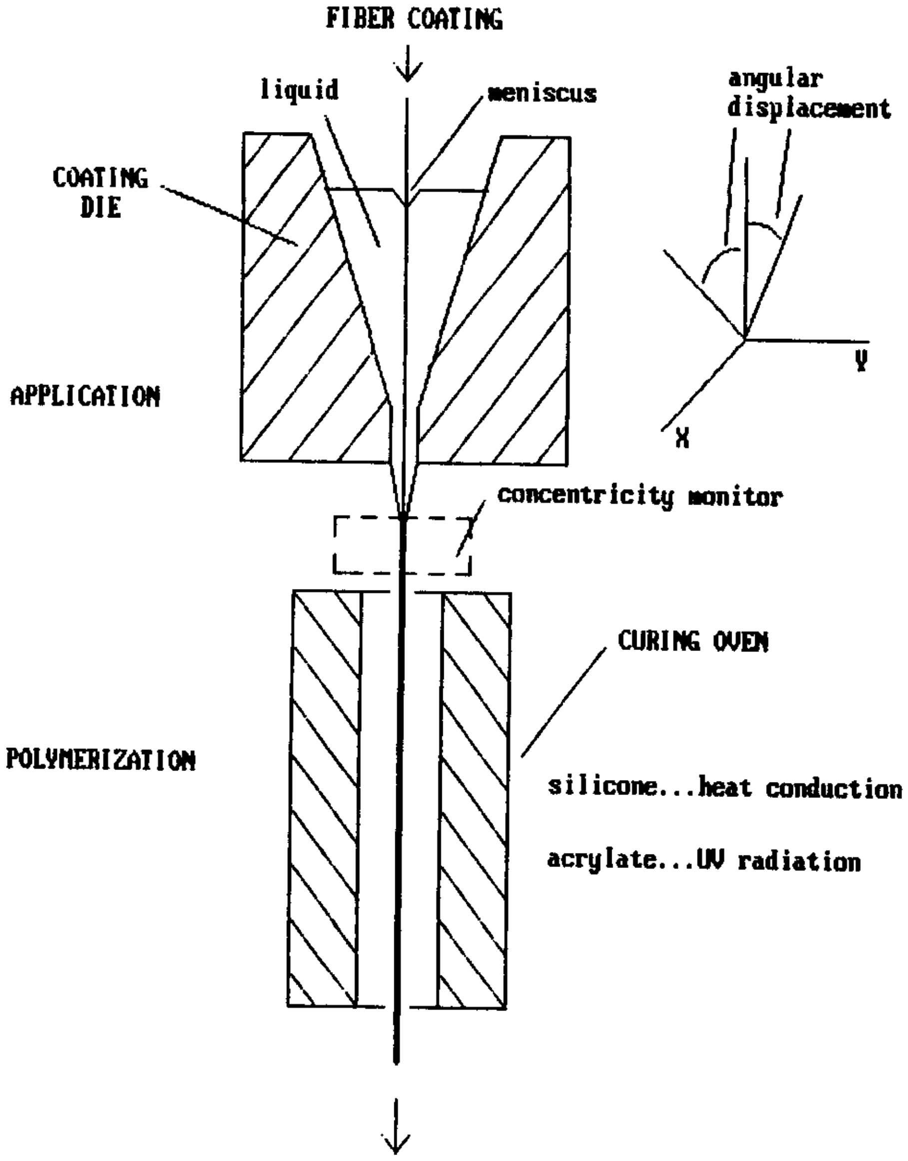
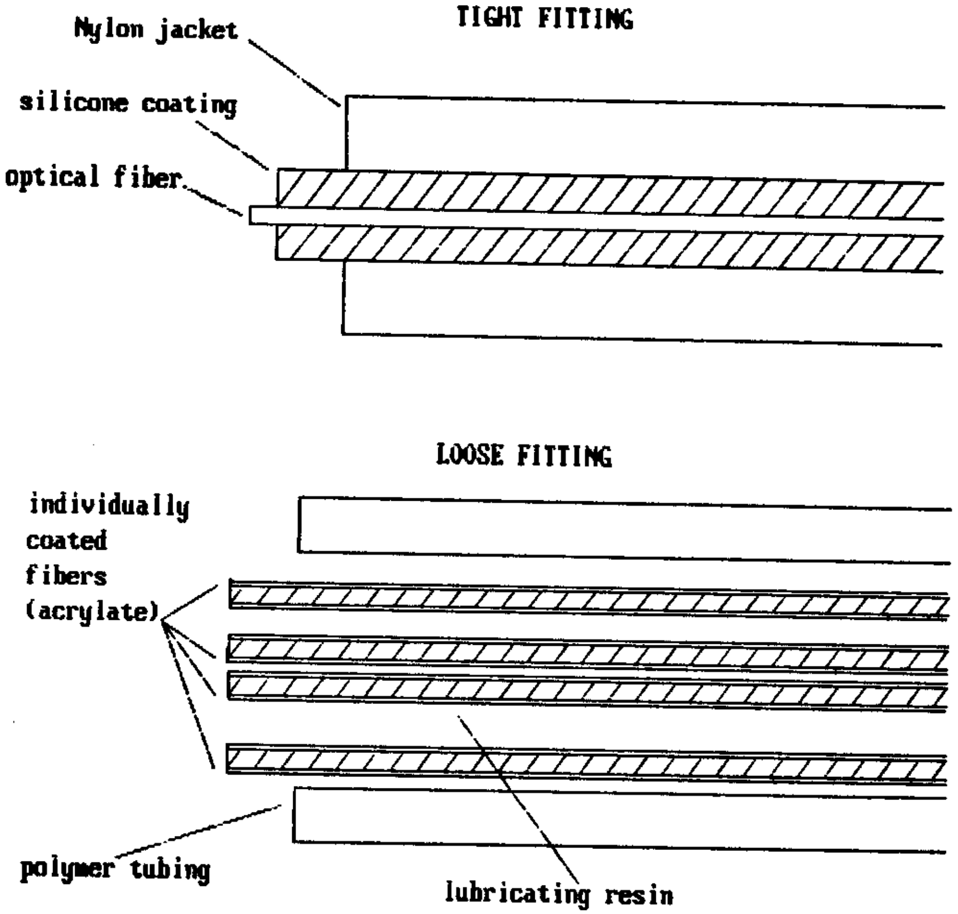
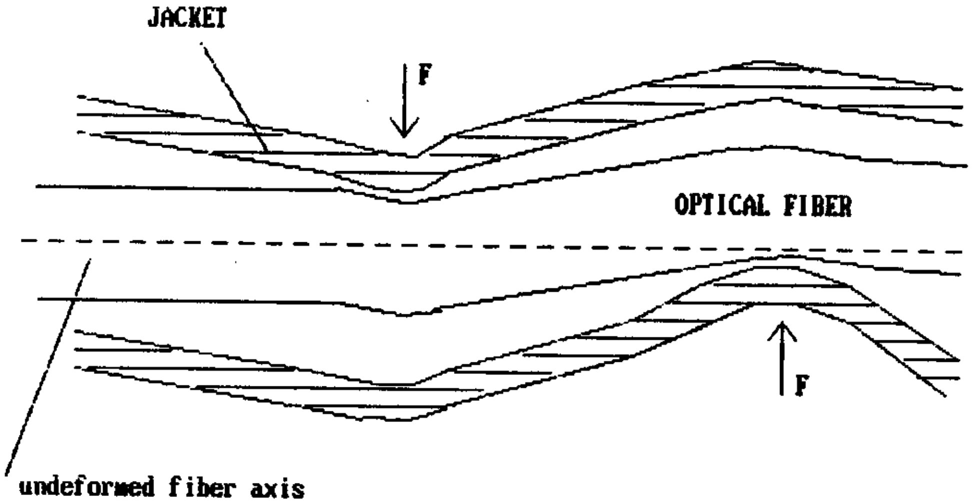


FIGURE 26

OPTICAL FIBER JACKETING



MICROBENDING LOSS



USUAL CAUSES

- LATERAL FORCES
- COMPRESSIVE STRESSES DUE TO DIFFERENTIAL THERMAL CONTRACTION
- POOR CABLE DESIGN