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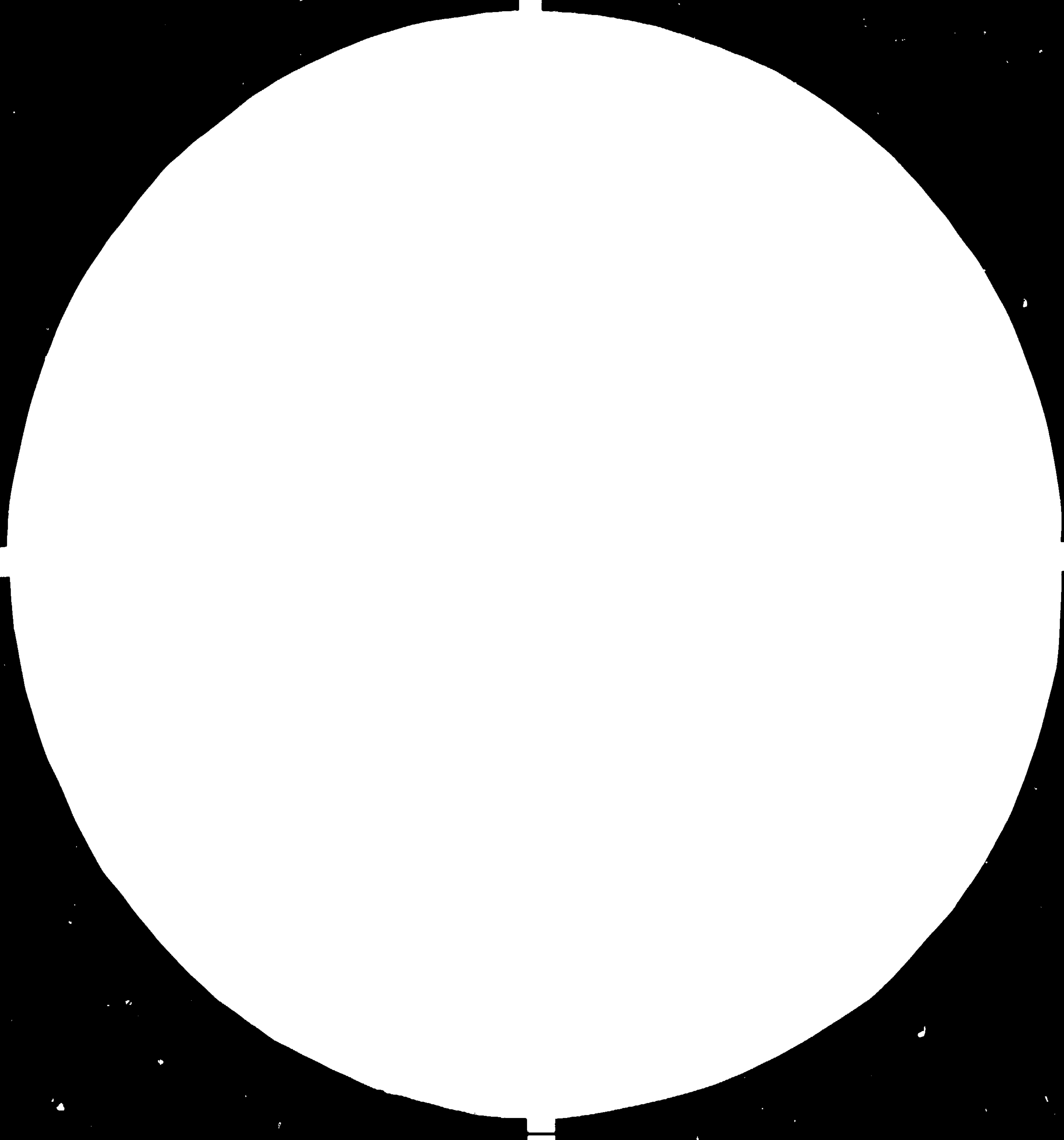

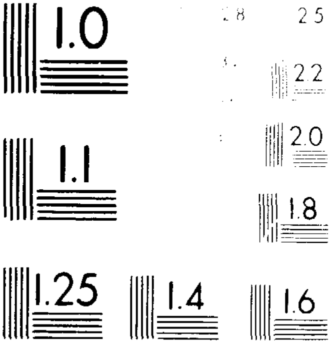

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OPTICAL FIBER PRODUCTION

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Abstract

The current status of technologies for production of optical fibers and cables is reviewed and trends of production and markets - and optical communications in general - identified. Specific requirements for the production of optical fibers are availability of pure gases and chemicals, familiarity with clean-room conditions, and qualified personnel in chemical, optical, communications and process control engineering. Bulk raw materials or a numerous labor force of unskilled workers is not required. Fabrication of cables from fibers poses less technological and financial problems, stipulating that conventional cable production is an established technology.

For threshold countries, a joint venture is a viable way for entering the optical fiber/cable market. For least developed countries, the import of a complete new production plant is the easiest but not a very profitable way.

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1. OPTICAL COMMUNICATIONS - BASICS AND TRENDS

1.1 Basics

The high carrier frequency of light promises a tremendously wide bandwidth for transmitting information compared with conventional systems. Whereas line-of-sight transmission through the atmosphere is restricted to some kilometers by the absorption of light due to dust, fog and rain, guided transmission of light through glass fibers became attractive in 1970, when Corning Glass Works announced the development of optical fibers with losses less than 20 dB/km /1/. Suddenly, long-distance telecommunications by fiberoptics seemed possible. The ensuing development of optical fiber transmission systems grew from the combination of semiconductor technology, which provided the necessary light sources and photodetectors, and optical waveguide technology upon which the optical fiber is based. In the last years world-wide research activities led to the development and installation of practical and economically feasible optical fiber communication systems operating as baseband systems in which the data are sent by simply turning the transmitter on and off.

The elements comprising an optical fiber transmission link are shown in Fig.1.1.

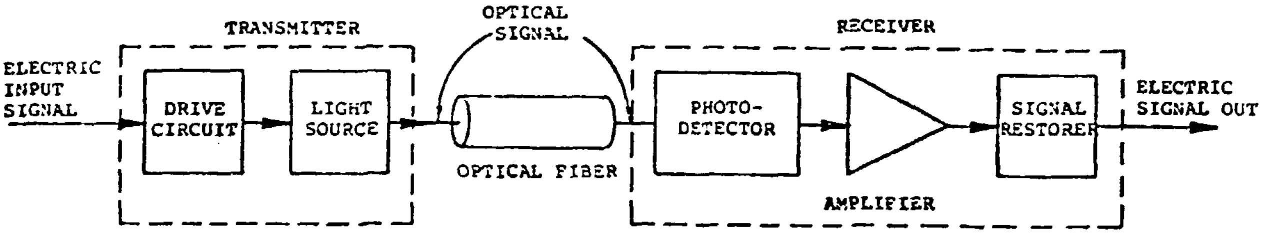

Fig.1.1: Basic elements of an optical fiber transmission link.

The key sections are

- a transmitter consisting of a light source and its associated drive circuitry

- a cable offering mechanical and environmental protection to the optical fiber(s) contained inside, and
- a receiver consisting of a photodetector plus amplification and signal-restoring circuitry.

The light sources suitable for fiberoptic transmitters are semiconductor injection laser diodes and light-emitting diodes (LED). They have adequate output power, which can be directly modulated by varying the input current to the device, they have a high efficiency, and their dimensional characteristics are compatible with those of optical fibers. In the 800 to 900 nm region the light sources are generally made of alloys of GaAlAs. At the longer wavelengths ($\lambda = 1100$ to 1600 nm), InGaAsP alloys are the suited material. A major difference between LEDs and laser diodes is that the optical output from a LED is incoherent, whereas that from a laser diode is coherent. Coherence means that the light is highly monochromatic and that the output beam is highly directional. Since a LED has no wavelength selective cavity its optical radiation has a broad spectral width and a large beam divergence.

Generally, the cable contains several hair-thin glass fibers, each of which is an independent communication channel, and, if necessary, copper wires for powering repeaters which are needed for periodically amplifying and reshaping the signal when the link spans long distances. An optical fiber is a dielectric waveguide operating at optical frequencies. Its form is normally cylindrical. It confines electromagnetic energy in the form of light to within its surfaces and guides the light parallel to its axis due to total internal reflection /2/. As illustrated in Fig.1.2 the fiber consists of a solid core surrounded by a cladding having a lower refractive index than that of the core. An elastic plastic buffer encapsulates the fiber for higher strength and mechanical isolation from the cable structure.

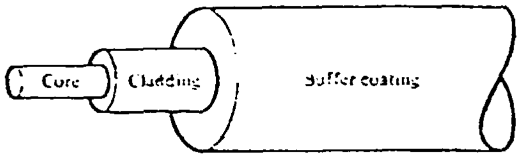

Fig.1.2: Schematic of a single-fiber structure. A circular solid core (n_1) is surrounded by a cladding having a refractive index $n_2 < n_1$. An elastic plastic buffer encapsulates the fiber.

The installation of optical fiber cables can be either aerial, in ducts, undersea, or buried directly in the ground. As a result of installation and/or manufacturing limitations, individual cable lengths will range from several hundred meters to several kilometers. The complete long-distance transmission line is formed by splicing together these individual cable sections.

The photodetector senses the luminescent power falling upon it and converts the variation of this optical power into a correspondingly varying electric current. Of the semiconductor-based photodetectors, the photodiode is used almost exclusively for fiber optic systems because of its small size, suitable material, high sensitivity, and fast response time. The two types of photodiodes commonly used are the pin photodiode and the avalanche photodiode (APD). The materials are Si, Ge and InGaAs.

1.2 Comparison with conventional telecommunications

The advantages of fiber optic transmission compared with conventional electrical telecommunication (twisted wire pair, coaxial cable, microwaves) are /3/:

- An extremely wide bandwidth means that a greater volume of information or conversations can be carried over a particular transmission line.
- A very low attenuation reduces the number of repeaters, or makes them completely obsolete. Figure 1.3 compares the transmission performance of optical fibers with copper coaxial tubes.

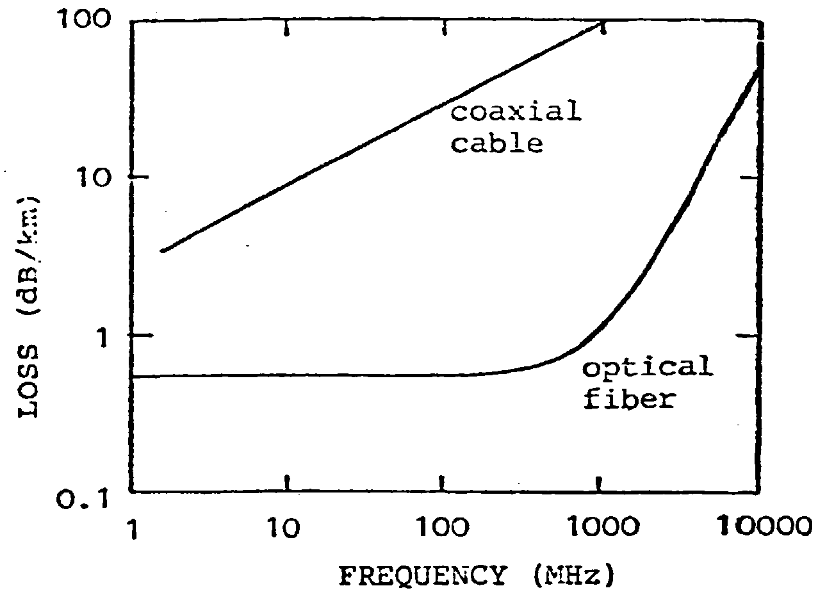

Fig. 1.3: Transmission performance of optical fibers compared with copper cables (attenuation/km vs frequency) /4/.

- Small-diameter, lighter-weight cables are obvious advantages with the hair-thin fibers. Together with the size reduction (easily 10:1) goes an enormous reduction in weight (25:1), which is an important advantage in aircraft, satellites and space vehicles, ships, and high-rise buildings.

- Negligible crosstalk with fiber optics even when numerous fibers are cabled together and almost total immunity to wiretapping provide greater security.

- Immunity to radio-frequency interference (RFI), electromagnetic interference (EMI), or electromagnetic pulses (EMP).

- Greater safety (light, not electricity, is being conducted) and electrical isolation between the transmitter and the receiver.

- High tolerance to temperature extremes as well as to liquids and corrosive gases.

- At present the existing price penalty prevents optical fibers from completely driving copper lines out of business.

1.3 Applications and trends

Two main tasks can be catagorized for telecommunications systems:

- point-to-point transmission of data
- multi-user - multiservice distribution of data

A finer structuring of these two main tasks is presented in Fig.1.4.

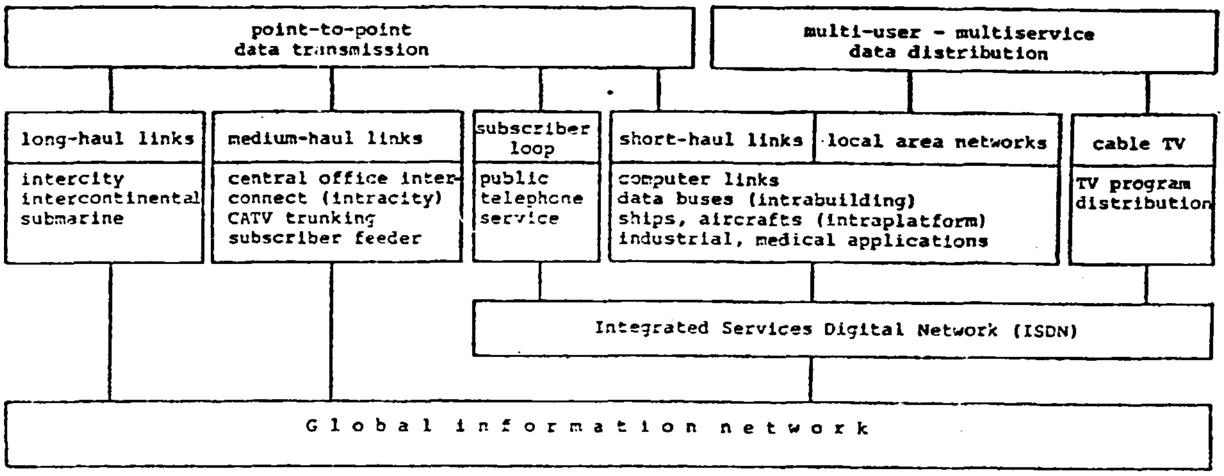

Fig.1.4: Classification of tasks in telecommunications.

Depending on the intended area of use there are different features of optical fibers which give an advantage of optical fibers over conventional systems. In transmission systems it is the low attenuation and the huge information capacity of optical fibers which makes them so attractive. For distribution systems the main advantage of optical fibers will be cost, weight, immunity to electromagnetic interference, and - so far broadband services have to be distributed - bandwidth.

The challenges of today's general telecommunication trends are:

- offer diversified communications services
- integrate services
- integrate components
- digitalize networks
- reduce cost of transmission

They are met by fiberoptics through pursuit of vigorous R&D with the aims and relevant activities summarized in Table 1.1.

Table 1.1: Summary of trends.

aims	activities	application areas to benefit from these developments
avoid repeaters	single-mode fiber 1550 nm wavelength: dispersion-shifted fiber single-frequency laser new materials for 2-5 µm low-noise PIN-FET receivers coherent detection	long-haul links
make optimum use of installed fiber by WDM[1]	ultrabroadband fiber frequency-stabilized laser	medium-haul links subscriber loop
benefit from electrical isolation, EMI-freedom, weight, volume	cheap passive and active components (Lasers, LEDs, photodiodes, couplers)	short-haul links LANs

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[1] WDM means wavelength-division-multiplexing. Light signals at different wavelengths are transmitted simultaneously on the same fiber.

2. CLASSIFICATION OF FIBERS - FIBER STANDARDS

Optical fibers can be classified according to the following criteria:

- type of light propagation
- material of core and cladding
- dimensions of core and cladding
- transmission characteristics

Grouping fibers by the way the light propagates in them, two principal kinds are distinguished:

- single-mode (monomode) fibers
- multimode fibers

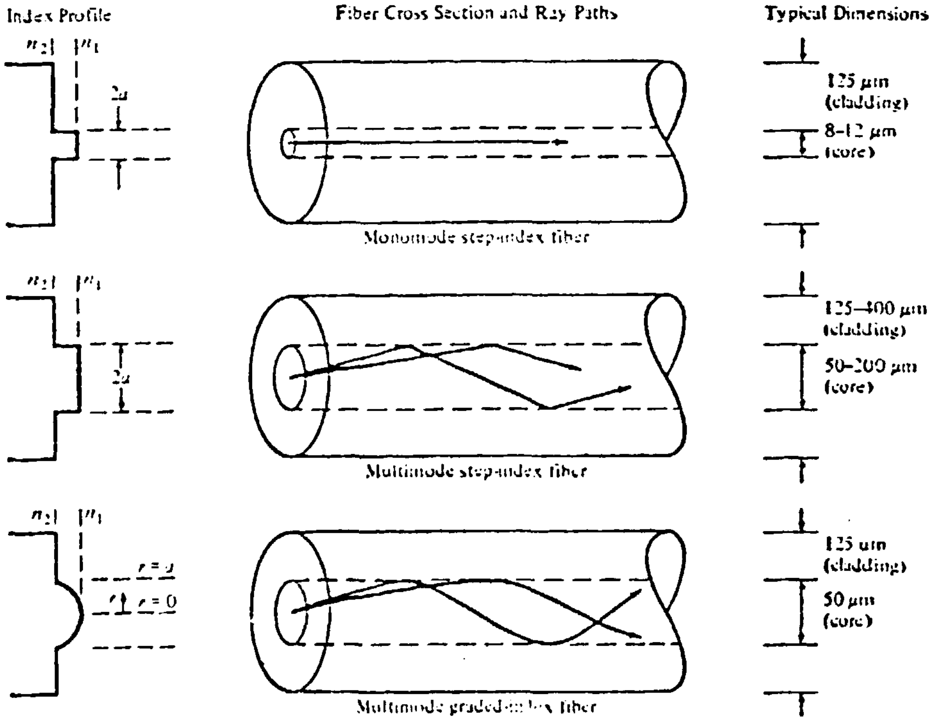


Fig.2.1: Comparison of step-index (single- and multimode) and graded-index optical fibers /2/.

Single-mode fibers usually are, as depicted in Fig.2.1, so-called step-index fibers (SI). In the radial direction the refractive index undergoes an abrupt step-like change at the core-cladding interface. Due to the core diameter chosen only the fundamental mode (= electromagnetic radiation pattern) is guided by this fiber type. The dispersion, which causes pulses traveling along the fiber to spread, and attenuation of the single-mode fiber is the lowest possible enabling high data-rate transmission over long distances without distorsion.

Multimode fibers, according to the refractive index profile of their cores, are either

- step-index fibers or
- graded-index fibers (GI).

A multimode fiber has a core of larger diameter than single-mode fibers and carries many hundreds of modes. The dispersion of the SI-multimode fiber is high, but is drastically reduced by a nearly parabolic variation of the refractive index profile (GI-fiber). By no means the low dispersion of single-mode fibers can be obtained.

The main advantage of multimode fibers is the considerably larger core diameter making it easier to launch optical power into fibers, expecially with LEDs. The large core reduces also the requirements on the tolerances of connectors and splices to join similar fibers.

A measure of the information capacity of an optical waveguide is usually specified by the bandwidth-distance product in MHz x km. For a step-index fiber the various distortion effects tend to limit the bandwidth-distance product to about 20 MHz x km. Graded-index fibers exhibit a value as high as 2.5 GHz x km. Single-mode fibers can have capacities well in excess of this.

The material of core and cladding may be glass or plastic and divides fibers into the following major categories (Table 2.1).

Table 2.1: Categories of multimode fibers by material of core and cladding (Single-mode fibers always have glass core and glass cladding).

core	cladding	category[1]
glass	glass	A1: graded index
		A2: step index (quasi step index)
glass	plastic	A3
plastic		A4

[1] According to IEC Document 46E(CO)8.

Among the useful glasses, fused silica (SiO_2) in pure and doped form ranks first in production of low-loss fibers. Other glass compounds, made e.g. by addition of Na_2O+CaO or $Na_2O+B_2O_3$, lower the high process temperatures necessary for pure silica, but usually result in higher optical loss of the fibers. Plastic materials suitable as cladding of glass fibers (plastic coated silica, PCS fibers) include /5/ low-loss silicone resins and fluoridized polyalkenes and polymethylacrylates. All-plastic fibers suffer of very high loss (100 ÷ 1000 dB/km) which is the reason for no wide-spread use in telecommunications.

The dimensions of core and cladding are closely related to the type of light propagation and to the fiber materials (see Fig.2.1). Up to now there exists no complete standardization of the dimensions of optical fibers. Both IEC standard and CCITT recommendation stress that setting the 50/125 µm standard does not preclude other, future standardized dimensions of A1 fibers. In fact, the dimensions 85/125 µm and 100/140 µm have been recently proposed and are under consideration /6/.

The second standard in effect to date concerns category A3 fibers (plastic clad silica) /7/. Only the core diameter is specified as 200 µm.

For single-mode fibers there exist no international standards, but a cladding diameter of 125 µm ± 3 µm has been proposed in a CCITT draft recommendation /8/. Specifying a core diameter does not make sense, rather the mode field diameter is the relevant quantity. (For Gaussian light distribution, the mode field diameter is the diameter at the 1/e points of the optical amplitude distribution.) For an operating wavelength of $\lambda = 1300$ nm, parameter values of 9 µm ± 1 µm and 10 µm ± 1 µm have been proposed.

Transmission characteristics which are

- attenuation (in dB/km) and
- bandwidth (in MHz or MHz x km)

depend greatly on the wavelength used to convey the information. Figure 2.2 illustrates the wavelength regions of low fiber attenuation.

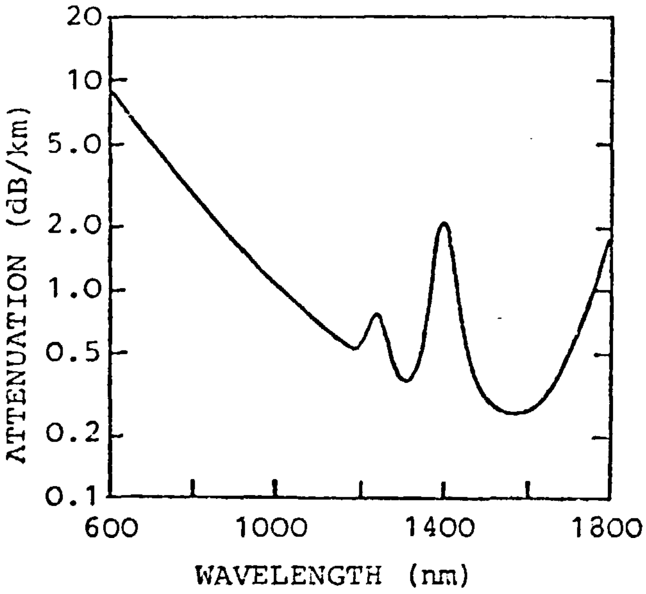


Fig.2.2: Optical fiber attenuation as a function of wavelength. Material research and improved fabrication methods (e.g. low OH content) reduced the attenuation especially at longer wavelengths.

Because of these attenuation characteristics, three wavelength regions are in use today, a forth one ($\lambda = 1550$ nm), where attenuation is a minimum, will be opened as R&D on fibers and components progress. Table 2.2 gives an overview on these regions.

Table 2.2: Wavelength regions for fiberoptics.

Wavelength region ("window")	Major use	Typical fibers
around 630 nm	short-haul data transmission	plastic
around 850 nm[1]	general purpose	graded-index glass, PCS, step-index glass
around 1300 nm[2]	long-haul trunk lines	graded-index silica, single-mode silica
around 1550 nm[3]	long-haul trunk lines	high-grade silica (single-mode)

1)2)3) Sometimes referred to as "first", "second", "third window", respectively.

A coarse classification of fibers according to their attenuation and bandwidth coincides with material, wavelength, and propagation classifications (Fig.2.3).

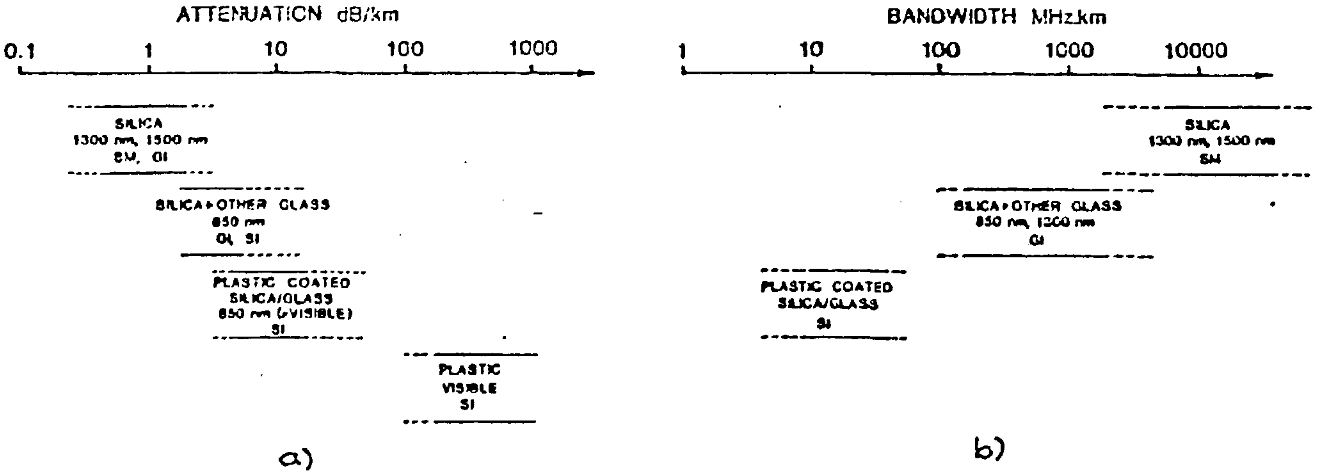


Fig.2.3: Attenuation (a) and bandwidth (b) of optical fibers
SM ... single-mode fiber
GI ... graded-index fiber
SI ... step-index fiber

3. PRODUCTION OF OPTICAL FIBERS

Basically, two paths can be followed to produce optical fibers (Fig.3.1):

- first preform fabrication, then fiber drawing
- direct drawing from the melt.

The "preform fabrication - then fiber drawing" approach is today's most widely accepted one for the production of

- high-quality silica fibers and
- plastic-clad silica fibers.

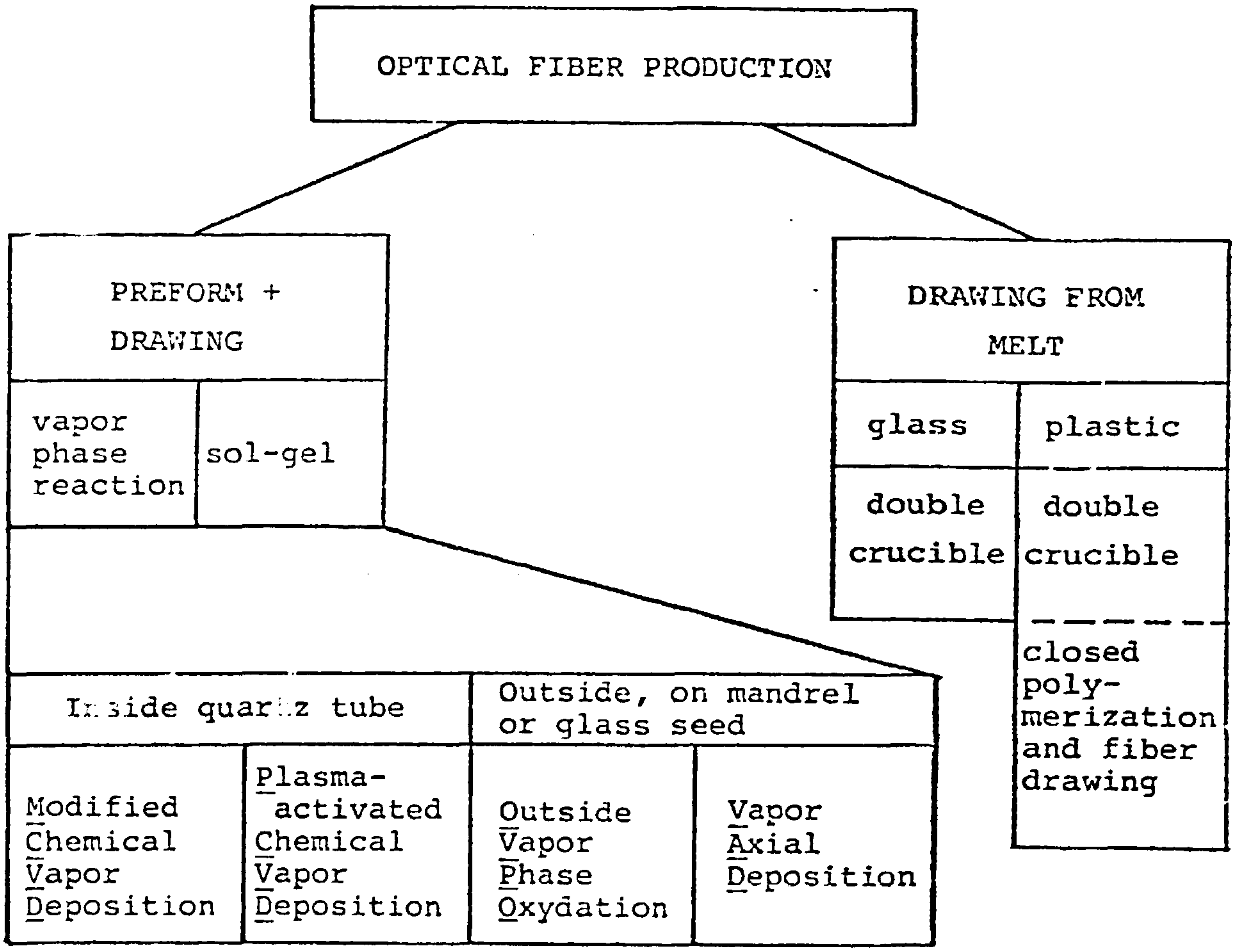


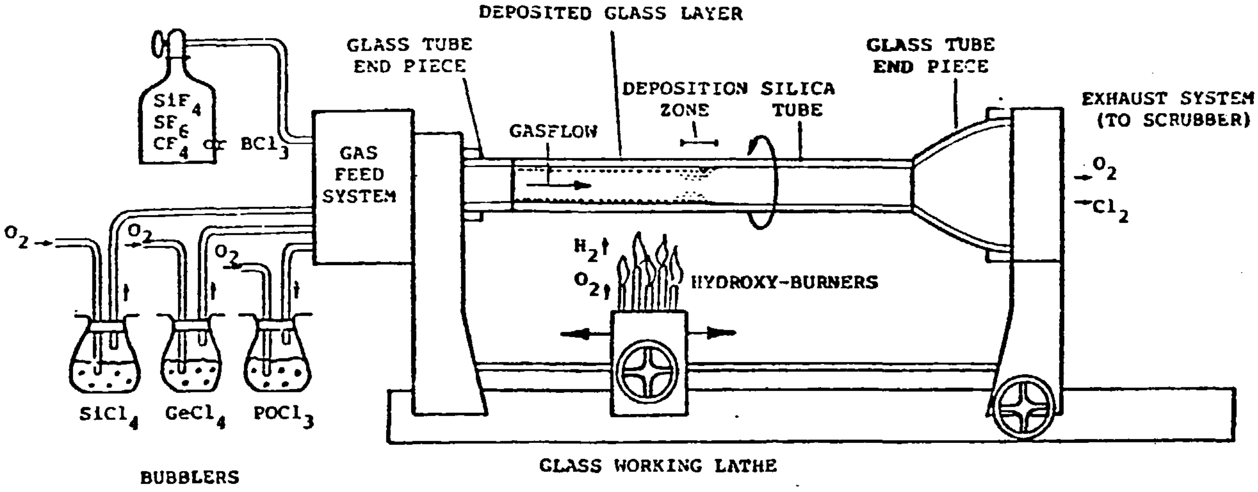
Fig.3.1: Classification of fiber production processes.

3.1 Preform fabrication

Making preforms for high-quality silica fibers (SiO_2), a general method called vapor-phase reaction, is used. Vapor-phase deposition and oxidation methods have originated in the semiconductor and glass industry and are applied in fiber preform fabrication for reasons of achievable purity and cleanliness. The major raw material for silica fibers is silicon tetrachloride ($SiCl_4$). The portions of the preform designated to form the future fiber core or the adjacent layers of the cladding are doped to increase (e.g. GeO_2, P_2O_5) or decrease (e.g. B_2O_3, F) the refractive index. Hard-glass fiber can therefore be said to be based on germanosilicate, borosilicate and phosphosilicate glass.

3.1.1 MCVD

MCVD stands for modified chemical vapor deposition. This process, developed at Bell Laboratories /9/ and subsequently applied and improved by many laboratories and factories all over the world, starts from a tube of fused silica which ultimately becomes the outer cladding of the fiber. High-grade silica tubes of dimensions 25 mm outer diameter, 19 mm inner diameter and 1000 mm length are standard. The OH content of the - predominantly used - Heralux WG tubes of Heraeus, Hanau, West Germany, is 150 ppm. The tube is then mounted in a glass working lathe to be rotated and heated by one or several oxyhydrogen torches (Fig.3.2). A gas stream consisting of a carrier gas and halide vapors is fed into the tube and passed through it. Gas phase reaction of halides and oxygen in a zone heated from the outside by the torch forms glass particles which are deposited downstream of the torch position. Since the torch is traversed in the direction of the gas flow, the deposited layer is sintered immediately after deposition. Typically, 30 to 100 layers are deposited by as many passes of the torch. The composition of the layer can be varied during each traversal by addition of dopants to the gas stream. Finally, the tube including the deposit is collapsed into a solid rod, the preform, again by outside heating to silica softening temperature (1900 - 2200°C).



ig.3.2: Schematic of MCVD apparatus.

To enhance the deposition efficiency of MCVD, RF-plasma-enhanced MCVD has been proposed /10/. The steps "particle deposition" and "consolidation" are performed by separate heat sources.

It is estimated that a total of 1500 - 2000 manyears have so far been invested into the development of MCVD. This process is well documented. It has found widespread use all over the world and is probably the easiest process to set up.

3.1.2 PCVD

PCVD stands for plasma-activated chemical vapor deposition. This process was pioneered by Philips /11/. The main difference (and advantage) of PCVD as compared to MCVD is that a non-isothermal plasma (Fig.3.3) initiates a reaction on the inner wall of the tube. No "soot" is formed, because the temperature of the furnace in which the process occurs is too low. PCVD is a "low-temperature" process. Deposition efficiency of SiO_2

and GeO_2 occurs heterogeneously (i.e. only on the tube wall) upon initiation of the plasma. A microwave resonator sweeps passed the tube, and very thin layers (~0.5 µm) are deposited at each pass. Several hundred layers are usual, permitting very close profile control.

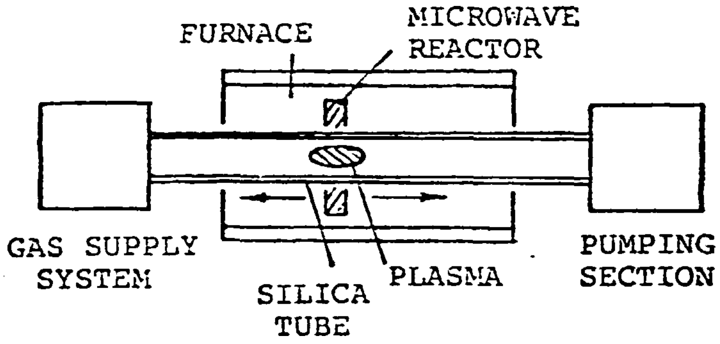


Fig.3.3 Schematic of PCVD process.

Some 500 manyears have been invested in the development of this process. Control of process parameters is claimed to be easy.

3.1.3 OVPO (OVD)

Outside vapor-phase oxidation was invented by Corning Glass Works /13/. This company prefers to name the process outside vapor deposition (OVD). Figure 3.4 shows the schematic of the - separate - deposition and of the sintering (= consolidation) steps. The essential difference to MCVD and PCVD is the lateral outside deposition of glass particles. These glass particles (~0.1 µm in average diameter) stick together to form a porous preform around the center starting member of Al_2O_3. After removal of this member, a sintering step transforms this porous or soot preform to a transparent glassy preform, from which the fiber is eventually drawn.

Investment in total manpower for development is estimated between 600 - 800 manyears.

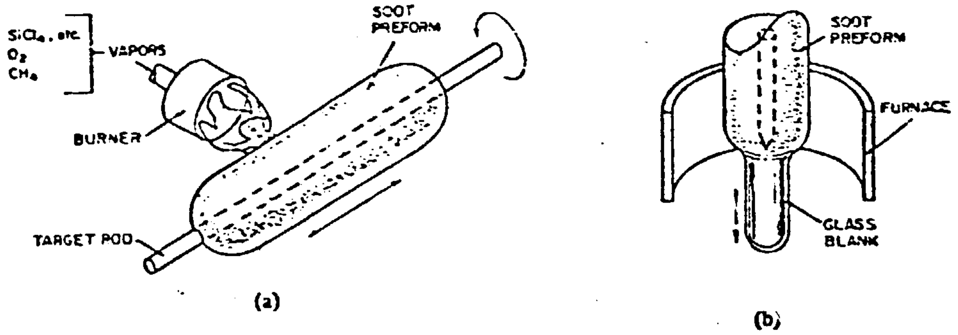


Fig.3.4: Schematic of OVPO process /13/
(a) Deposition
(b) Consolidation.

3.1.4 VAD

In the processes described so far, glass layers are deposited in lateral direction. In the vapor-phase axial deposition process, glass particles are deposited onto a rotating vertical seed rod from below (Fig.3.5). As in the OVPO process, glass particles are synthesized in the flame of an oxyhydrogen burner. In this way a porous preform (soot preform) grows in axial direction. It is gradually pulled up in accordance with this growth so that the burner position remains unchanged. The soot preform has to be consolidated to the transparent actual preform for fiber drawing. The VAD process was developed by Ibaraki Electrical Communications Laboratory (Nippon Telephone and Telegraph Public Corporation) /14/ and is used by the major Japanese fiber producers (Sumitomo, Furukawa, Fujikura).

Approximately 1000 manyears have been consumed by development of this process.

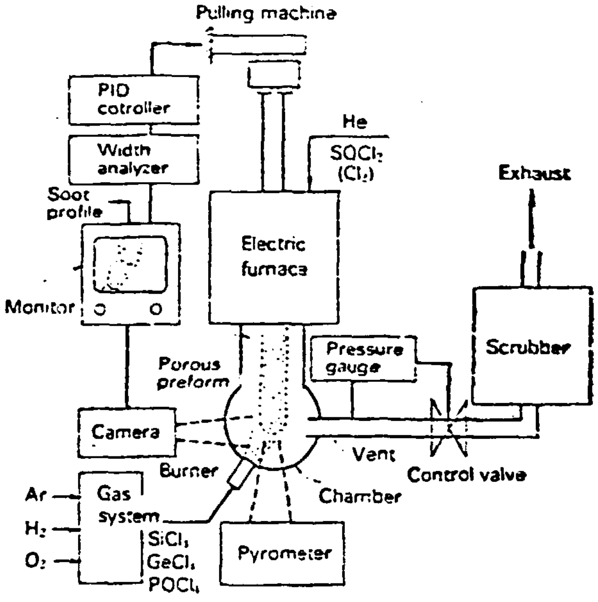


Fig.3.5: Schematic of VAD apparatus /15/.

3.1.5 Comparison of CVD processes

Advantages/Potential of MCVD

- inside tube deposition → little contamination
- partly porous deposition → partial OH removal possible
- flexible, well-understood, easy-to-model process

Limitations/Problem areas of MCVD

- discontinuous process
- requires high-grade silica substrate tube
- very low GeO_2 deposition efficiency (10 - 20%)
- length taper of index profile
- central dip of index profile
- preform size limited (fiber length)

Advantages/Potential of PCVD

- low deposition temperature
- inside tube deposition → little contamination
- no length taper
- highest deposition efficiency
- relaxed temperature control (± 5° at deposition)
- good dimensional control
- no heating through tube walls

Limitations/Problem areas of PCVD

- discontinuous process
- deposition rate limited (low-pressure process)
- hydrogen incorporation
- preform size limited (fiber length)
- silica tubes necessary

Advantages/Potential of OVPO

- good profile control
- no collapse step necessary, but added complexity in drawing
- tolerant to hydrogen contamination in starting materials
- no silica tubes needed
- good dimensional control (tolerances, little ovality and excentricity)
- high deposition rate possible
- large preforms possible

Limitations/Problem areas of OVPO

- drawing with central hole requires control of atmosphere
- build-in stress of preforms (yield?)
- control of deposition complex

Advantages/Potential of VAD

- continuous process possible
- lowest OH level achieved
- tolerant to hydrogen contamination in starting materials
- large preforms possible (100 km fiber drawn)
- no collapse step necessary
- no silica tubes needed
- high deposition rate possible

Limitations/Problem areas of VAD

- index profile control difficult and critical
- soot density fluctuations
- roundness control
- fluorine doping difficult

3.1.6 Sol-gel process

A glass preform fabrication method entirely different from CVD is the sol-gel process /16/. It consists of the following steps: (i) hydrolysis of metal alkoxides to make a gel containing water and a solvent (methanol); e.g. tetra methoxysilane [$Si(OCH_3)_4$] : water : methanol in molar ratio 1 : 4 : 4.5, cast into cylindrical glass containers; (ii) drying of the gel to form a porous gel body (one week at $70^{\circ}C$); (iii) a chlorination process to reduce the initially high (~1000 ppm) OH content; (iv) sintering of the porous gel body to produce a transparent glass preform, which is performed at only $1100^{\circ}C$ under a He atmosphere to form a pore-free glass. The main advantages of this method are:

- low-temperature
- potential of mass production.

Nevertheless, the process has been used so far in the laboratory only.

3.2 Fiber drawing

Irrespective of the preform fabrication method, fiber drawing is achieved on drawing towers (Fig.3.6), at the top of which the preform is heated to silica melting temperatures ($<2200^{\circ}C$). When a refractive index profile has been incorporated into the preform, this profile is preserved in the drawing step. The drawing process includes several separate operations, all of which have to be carefully controlled /17/:

- heating of the preform
- drawdown of the molten glass
- monitoring and control of fiber diameter
- application of coating
- monitoring and control of coating thickness/concentricity
- solidification of coating
- fiber take-up.

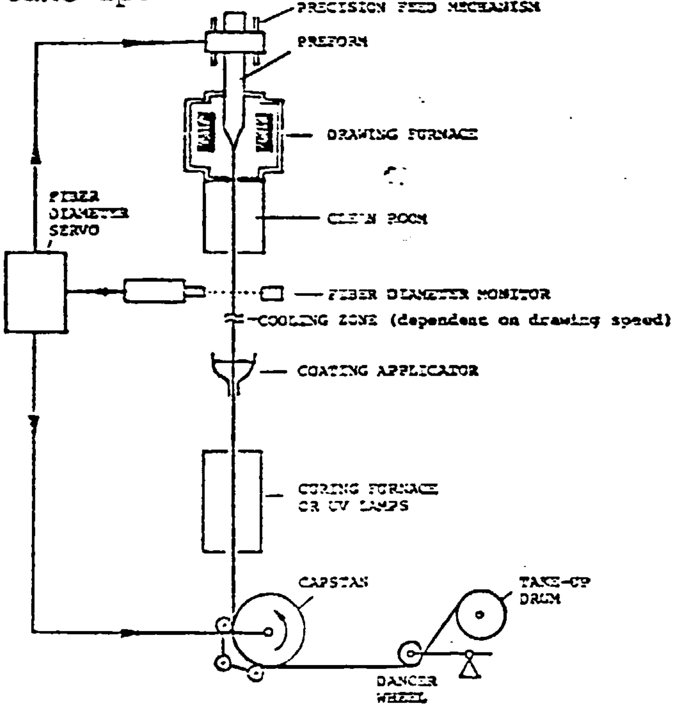


Fig.3.6: Schematic of fiber drawing tower.

For protection against damage and contamination, one or more primary <u>coatings</u> are applied to the just-drawn fiber. Most common coating materials (Table 3.1) are acrylates, which become hard upon curing by ultraviolett light, and silicone polymers, which are heat-treated after application but stay more or less soft. The coating process is the limiting factor to fiber drawing speed. First, the fiber has to cool down to a certain temperature before being ready to be coated. Second, the speed of the fiber through the coating cup or die must be low enough to ensure proper wetting. Third, the coating has to cure.

Table 3.1: Comparison of coating systems.

Materials	silicone rubber (e.g. poly-dimethyl siloxane, poly-methyl-phenyl-siloxane)	acrylate (e.g. urethane acrylate, epoxy-acrylate polymers, methyl-butadien-acrylate)
Curing	(usually) by heat	by UV radiation
Speed of coating process	1 - 2 m/s (5 m/s)[1)]	1 - 5 m/s (12 m/s)[1)]
Diameter of coating	0.25 - 0.4 mm	0.25 - 0.5 mm

1) laboratory results

The two important fiber properties influenced by the coating and jacketing steps are:

- fiber strength
- fiber loss (microbending).

3.3 Plastic-clad silica fibers (PCS fibers)

PCS fibers are designed as SI fibers, the core - a popular choice is natural quartz - has uniform refractive index. This rod is drawn to a fiber as described in Section 3.2. The cladding is a relatively low-loss polymer with a lower refractive index and is preferably applied by the methods similar to the coating process (Section 3.2), which requires a curable liquid as cladding material. For low-price applications purely plastic fibers will be prefered.

3.4 Drawing from the melt

The methods relying on melting basic raw materials and pulling the optical fiber directly from the melt are applied to both glass and plastic fibers. For such glass fibers, various oxides and carbonates are added to SiO_2 to form a multi-component glass with lower melting temperature than pure SiO_2. Core and cladding melts are loaded into double crucibles with two coaxial nozzles at the base, hence "double-crucible" method /18/. A number of major optical fiber manufacturers have discontinued using this method, since some severe disadvantages do not outweigh the advantage of this approach which is basic simplicity.

Plastic fibers are produced by very similar methods, but crucible material requirements are not so demanding because of lower melting points of the starting materials than glass. A modern variant of plastic fiber production by this method is the "closed polymerization and fiber drawing" method. It considerably reduces contamination of the starting materials and thus fiber loss.

3.5 Conclusive remarks to the production of optical fibers

Performance of optical fibers depends largely on the fiber production process and the materials used. Raw materials should be as pure as possible to prevent light absorption and scattering. Contamination during manufacture should be kept as low as possible to ensure a high-quality end product. As an example, a transition metal concentration of as low as 1 part per million causes additional absorption loss of 1 dB/km in silica. Even worse, the same OH concentration causes 35 - 50 dB/km loss at 1.39 µm wavelength!

From a purely economic point of view,

- yield and
- production speed

are important assessment criteria. Yield is to be understood as the output of fiber of given technical parameters as compared to input raw materials. Main criteria by which the quality of the produced fiber will be judged are:

- attenuation
- bandwidth
- mechanical strength.

In the production of hard-glass fiber preforms, which make up the overwhelming share of today's fiber market, several trends to increase productivity can be observed:

- increase of deposition rates (combine high deposition rate with large fiber bandwidth)
- increase of preform size (while maintaining high yield)
- increase of yield by improving or circumventing critical process steps
- making preform fabrication a continuous process
- elimination or combination of production rate-limiting steps (e.g. collapse)
- replacement of costly materials (high-quality silica tubes and $GeCl_4$, in first place)
- improvement of process control to consistently get high-quality fiber product
- replacement of P and B as dopants. Fluorine and Al_2O_3 are favorite candidates for lowering or raising the refractive index, respectively.
- elimination of the 1.39 µm OH peak and reduction of OH content in general
- further reduction of fiber attenuation at 1.55 µm wavelength for ultra-long range fiber systems
- development of entirely different methods of preform production (e.g. sol-gel process).

4. PRODUCTION OF OPTICAL CABLES

4.1 Mechanical fiber properties

Optical fibers cannot be handled straight-forwardly like copper wires, since, compared with metal, glass fibers differ considerably in the mechanical properties. Under an applied stress glass will extend elastically up to its breaking strength, whereas metals can be stretched plastically well beyond their true elastic range. Copper wires, for example, can be elongated plastically by more than 20 percent before they fracture. For glass fibers elongations of only 0.5 to 1.0 percent are possible before fracture occurs. In contrast to strength which deals with instantaneous failure under an applied load, static fatigue relates to the slow growth of preexisting flaws in the glass fiber under humid conditions and tensile stress. This gradual flaw growth causes the fiber to fail at a lower stress level than that which could be reached under a strength test.

These typical properties of the glass material and the small cross-sectional area of the individual fibers are responsible for their susceptibility to breakage and damage during the cabling and installation procedure. To provide the bare fiber with invulnerability and ruggedness the fiber has to be protected by a jacket and, afterwards, incorporated into a cable structure. In doing so, considerable attention has to be paid to minimizing additional optical losses due to stress which might be introduced during cable making and installation or, after installation, by environmental and mechanical factors.

4.2 Fiber jacketing

Despite the primary coating, which is applied immediately after the drawing process and consists of one or two layers of silicone or UV curable acrylate, the optical fiber is too fragile and vulnerable to damage by externally-induced stress or hostile environments. For further protection three packaging philosophies have been developed /19/:

- In the tight-fit jacketing approach a relative thick secondary coating of plastic is applied over the primary coated fiber, its main purpose being to enhance the tensile strength and to provide radial protection. Adequate mechanical protection is obtainable with nominal coating diameters in the range of 0.8 - 1 mm. A number of high modulus plastics have been used for secondary coatings, including amorphous polyethylene tetrephtalate (polyester), polypropylene, and nylons. For easy identification during installation and repair the jacket may be colorcoded.

- The loose-tube approach has been developed as a means of isolating the fiber from strain in the coating. In loose structures, the optical fibers are incorporated in platic tubes with a certain amount of slack and can move freely within limits. As a result, they are decoupled from tensile stresses during cable laying and during temperature-driven cable stretching and shrinking. The inner diameter of the tube is much larger than the 250 µm-diameter of the primary-coated fiber. The remaining space is filled with a water-blocking jelly. A higher fiber packing density than with only one fiber contained in one tube can be realized by stranding up to ten primary-coated fibers and protecting them by an extruded loose-fit plastic tube. For the loose-tube jacketing only UV curable acrylates can be used since this material ensures low friction of the fiber inside the tube.

- The open-channel approach is - in respect to the effect of isolating the fiber from strain in the coating - similar to the loose-tube approach. The difference, however, is that no additional plastic tube is formed to take up the fiber(s). The protection for the fibers is provided by the cable structure itself where channels or slots are formed to take up the fibers.

The loose-tube as well as the open-channel construction offer the lowest possible cable attenuation for a given fiber plus a high level of isolation from external tensile forces. This means more stable transmission characteristics under continuous mechanical stress. The tight-buffer construction permits smaller, light-weight design for a similar fiber configuration and generally yields a more flexible, crush resistant cable.

4.3 Cable design

To meet the requirements set by the cable customers (buyers) which converge in the wish to install fiberoptic cables with the same equipment, installation techniques, and precautions as those used in conventional wire cables, special cable designs are necessary ensuring that fiber elogations are limited to 0.1 to 0.2 percent /2/. The cable structures will vary greatly, depending on whether the cable is

- pulled into underground or intrabuilding ducts,
- buried directly in the ground,
- installed on outdoor poles (aerial cable),
- fixed to high-voltage lines,
- laid on intrabuilding grids,
- submerged under kilometers of water (submarine cable).

Whereas in copper cables the wires themselves are generally the principal load-bearing members of the cable, in fiberoptic cables special strength members have to be added to take up the axial load, like:

- steel wires
- plastic monofilaments
- textile fibers (Terylene, Dacron, Kevlar)
- glass fibers
- fiber reinforced plastics (FRP)

High modulus materials are inherently stiff in the solid form, but flexibility can be improved by employing a stranded or bunched assembly of units of smaller cross section, preferably with an outer coating of extruded plastic, helically applied tape, or a braid. Such a coating is particularly necessary if the strength member comes into contact with coated fibers since a resilient or smooth contact surface is required to avoid optical losses due to microbending. The position of the strength members can be the center of the cable or the strength members can be placed around the fibers.

Another factor to consider is fiber brittleness. Since glass fibers do not deform plastically, they have a low tolerance for absorbing energy from impact loads. Hence, the outer sheath of an optical cable must be designed to protect the glass fibers inside from lateral impact forces. In addition, the outer sheath should not crush when subjected to side forces, and it should provide protection from corrosive environmental elements. In underground installations, a heavy-gauge-metal outer sleeve may also be required to protect against potential damage from burrowing rodents.

The simplest cable design are so-called fiber cords containing one or two fibers intended for indoor use connecting data terminals or measurement equipments. The cable length is some meters. Usually both ends are provided with connectors. Such cables are called "jumpers". For strength purposes this tube is surrounded by strands of polyaramid yarn which, in turn, is encapsulated in a polyurethane jacket.

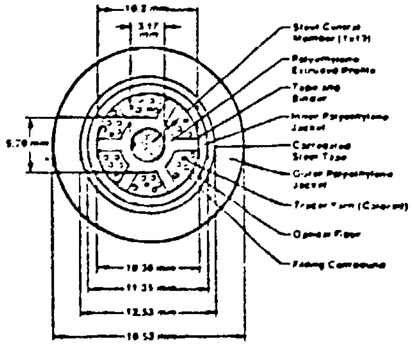


Fig.4.1: Slotted-core cable design /19/.

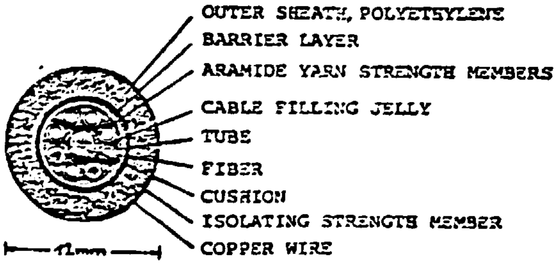


Fig.4.2: Six-fiber cable based on the loose-fit tube /20/.

In the telecommunications industry larger cables containing up to thousands of fibers are required. Three different basic cable structures can be distinguished:

- The slotted-core cable: Helically wound slots (typically six to twelve) are formed by extruding hot plastic through specially-designed dies around the strength member. Into these open channels up to twelve fibers are laid simultaneously and tension-free. They are kept in place by applying a closely spaced dual binder yarn around the plastic profile (Fig.4.1). If water-blocking is required, a gel is filled into the void of each slot.

- The stranded circular design: Several basic fiber units (loose tube or tight-jacketed) are stranded around a central strength member (Fig.4.2).

- The rectangular ribbon array cable: Twelve coated fibers are embedded in a PE-tape. Twelve of these ribbons are stacked together producing a fiber array. Then, this stacked ribbon array is stranded together with strength members and is sheathed.

For the cabling of optical fibers conventional basket cabling machinery as used in the cabling of metallic wires has been successfully adapted. Since attention has to be paid to apply a uniform tension of the fibers to be stranded, special fiber stranding machines have been developed. A new stranding principle is the "SZ-stranding technique" /20/.

5. TESTING AND QUALITY CONTROL

Fiber optics is one of the world's fastest developing technologies and the test equipment/methods are undergoing an equally rapid development. Although, there are still some unresolved technical problems associated with transmission measurement methods, some standard test methods for fibers have evolved and international standardization is impending, expecially for GI-fibers /21,22/.

5.1 Fiber testing

It would be desirable to test only selected specimens of the fibers produced. Inevitable variations of the production process, however, preclude this economical procedure and every meter of fiber produced must be thoroughly tested for /23,24/:

- strength
- attenuation
- bandwidth (= baseband response)
- numerical aperture
- size (core diameter, refractive index peak change Δn,...)
- concentricity
- cut-off wavelength (SM fibers only)
- polarization characteristics (SM fibers only)

5.1.1 Strength

Two categories of tests pertain to fiber strength. First, every fiber has to undergo a screening test where the drawn fiber is wrapped - under defined tension - from one reel to another. This test detects and eliminates cracks and other physical defects simply by rupture. Second, tensile failure point of a selected number of fibers is determined as a measure of statistical quality control.

5.1.2 Attenuation

Optical attenuation is measured at the wavelength or in the wavelength region for which the fiber is intended. Because of today's low fiber loss a measurement uncertainty of 0.1 dB is desired. For consistent measurement results, the conditions of launching light at the fiber input have to be well defined ("equilibrium mode launching conditions" /21/). Three reference methods are recommended by /21/:

- cut back
- insertion loss
- backscattering

5.1.3 Bandwidth

The bandwidth (baseband response) of a certain length of fiber may be measured either in time domain or in frequency domain. The results of either method can be transformed into each other by a computer. The frequency domain measurement is more common, but it also requires sophisticated equipment, both optical and RF electronic. The optical wave is modulated by the swept baseband frequency. The frequency at which amplitude response is 6 dB (electrical) - or 3 dB (optical), respectively - below its DC value is called "bandwidth". It is given for a fiber length of 1 km.

5.1.4 Special tests on single-mode fibers

The actual core size, the numerical aperture, and the exact refractive index profile of SM fibers are difficult to measure routinely. Therefore it is customary to specify and to measure the mode field diameter instead /6/.

A parameter defining the useful wavelength region of an SM fiber is the cut-off wavelength λ_c of the first higher order mode (designated LP_{11}). For its determination a spectrally tunable light source is required. The simplest criterion by which to determine cut-off wavelength is bending loss: The fiber is wound around mandrels of 20 and 30 mm diameter and the respective spectral response is measured /25/.

5.2 Cable testing

After fabrication each cable has to be tested to ensure tight control of quality. The optical characteristics of the cable, especially the attenuation at the design wavelength, are evaluated using the same measurement techniques as those described for fibers. These measurements are required to be carried out while the cable is subjected to the conditions called for by the specifications. The mechanical tests are concerned with survivability of fiber when the cable is subjected to stresses at various temperatures and humidities. These mechanical/environmental tests are generally based on standard test procedures used in the copper cable industry /21/ and are listed in Table 5.1 and 5.2.

Table 5.1: Mechanical characteristics

Test number	Subject of test	Characteristics covered by test method
IEC XXE- 1	- Tensile strength	- Mechanical strength
- 2	- Abrasion	
- 3	- Crush	
- 4	- Impact	
- 5	- Radial Pressure	
IEC XXE- 6	- Bend	- Ease of handling
- 7	- Torsion	
- 8	- Vibration	
- 9	- Flexing	
-10	- Fiber constraint in cable	
-11	- Bend under tension	
-12	- Snatch	
-13	- Kink	

Table 5.2: Environmental characteristics

Test method	Subject of test	Characteristics covered by test method
IEC XXF-1	- High temperature - Low temperature	- Climatic performance
-2	- Temperature cycling	
-3	- Humidity	
IEC XXF-4	- Contamination	- Chemical resistance
IEC 68 Test J	- Mould growth	- Biological resistance
IEC 331	- Fire resistance	- Resistance to fire
IEC 332	- Propagation of fire	
IEC XXF-5	- Smoke emission	
IEC XXF-6	- Internal static pressure	- Pressure sensitivity
-7	- External static pressure	
IEC XXF-8	- Water penetration	- Resistance to water-penetration
IEC 189-1	- Cold bend	- Flexibility at low temperature
IEC XXF-9	- Freezing	- Freezing resistance
IEC XXF-10	- UV radiation	- Solar radiation resistance
IEC XXF-11	- Nuclear radiation	- Resistance to nuclear radiation

5.3 Quality control (QC)

The importance of QC in optical fiber production is evident. It should be stressed that there exists virtually no market for low-quality fibers. QC measures are to be taken before, during, and at the end of the production process.

Clean-room conditions are beneficial for a high-strength high-quality fiber. Preform fabrication, storage, and handling as well as fiber drawing should be performed in a controlled dust-free atmosphere. Within general areas of Class 10,000, special work places can then be raised to Class 100 by special clean-room booths if so desired.

Incoming raw materials are to be inspected. It has turned out sufficient to check the purity of delivered high-purity chemicals only in rather long intervals. For processes requiring substrate tubes, a very important measure of initial QC is the check of the tubes for uniformity of wall thickness, concentricity, ovality and bow.

During production of preforms, microcomputer control of gas composition, temperature, mass flow, burner traveling speed and the like is a good approach toward consistently high quality. For every fiber design, there exist (proprietary) "recipes" which are stored in a master computer. Though modeling of the various processes becomes more and more accurate, these recipes are still found largely by trial and error. The preforms for GI fibers are inspected for proper index profile by the method of /26/. As a QC measure this can eliminate faulty preforms before they are subjected to the drawing process.

A likewise general but effective measure to control and improve quality is an in-house R&D group. The secret of success of leading fiber companies is a large number of people in this area. For QC, their contribution is a basic and deep understanding of the physics and chemistry of the production process.

The most important step in QC is the final fiber testing. What really counts are the specifications of the fiber. Testing is becoming more and more elaborate, and the number of parameters measured increases. Fiber producers view this development with concern because every additional parameter measured will inevitably decrease yield. It is, of course, a reflection of the buyers' rising quality standards and again stresses the importance of QC in fiber production.

6. REQUIREMENTS

Optical fiber production has few but highly specific and out-of-the-ordinary requirements. Optical cable production, on the other hand, differs little from conventional cable production and has even relaxed requirements.

6.1 Basic requirements for fiber production

The basic requirements for fiber production are:

- ample supply of highly pure gases and other chemicals
- familiarity with clean-room conditions
- chemical engineers for setting up and supervising fiber production
- communication and optical engineers for the design of fibers and their testing
- general knowledge in the fields of electronic control engineering and computer-assisted automation of fabrication processes

6.2 Machinery and installations

The essential pieces of machinery of a fiber production facility are:

- gas feed/distribution system
- glass-working lathes
- fiber drawing towers
- optical/electronic test equipment
- computers for process control

Exact mass flow control of the pure gases of the burners is crucial for the production process. The feed system must be gas-tight and non-contaminating, and must provide exact mixing ratios and automatic switch-over when a cylinder/container becomes empty. Minute amounts of dopants must be reliably delivered to the carrier gas stream.

The glass-working lathes are the central parts of production units for the fiber preforms. Required length between centers is of the order of 1.5 m, inner chuck jaw diameter of a maximum 10 cm is sufficient. Turning speed is uncritical, but an automatic feed of a separate carriage for the oxyhydrogen burners is mandatory. An exhaust system channels solid particles, unreacted chemicals, and reaction products to a wet scrubbing system. Besides conventional filters, a water supply and a neutralization station is required.

Fiber drawing towers can be purchased "ready-to-use", but in-house designs (or at least modifications) are standard.

The testing of the drawn fibers involves sophisticated and expensive optical and electronic test equipment (see Ch.5).

Numerous sophisticated sensors and the process computers for the control of gas feed system, lathes, drawing towers and testing procedures make up for a considerable portion of the necessary equipment. The computer stores also the results of the final tests.

6.3 Pure gases and chemicals

The requirements for pure gases and chemicals are the most stringent and the most critical for optical fiber production. The purity of the critical constituents ($SiCl_4$, $GeCl_4$, O_2, He, Ar) should be as high as commercially available. Especially the H_2 and water vapor content has to be extremely low. Some gas suppliers specifically manufacture pure gases for the fiber optic industry. Usually the standard purity grades for CVD processes in the semiconductor industry are suited for optical fiber production.

Cooling water required in the deposition/consolidation step should be reasonably pure so that it neither attacks the glass tube nor the plumbing pipes.

6.4 Clean-room conditions/climatization

Although there is considerable controversy about the class of clean-room conditions required, there exists general agreement that cleanliness promotes eventual fiber quality. Preform production can be performed in rooms of Class 10,000 or worse with the glass-working lathes contained in air-tight boxes. Fiber drawing rooms should be of Class 1,000 to 10,000. The atmosphere around the just drawn fiber should be of Class 100. An air-condition system with control of temperature humidity and dust particles is required for the factory.

6.5 Electrical power consumption

Electrical power consumption is moderate, but electricity must be available permanently. If outages from the public mains are anticipated, an on-plant emergency power supply, e.g. by diesel powered generators, must be provided.

6.6 Labor force

The requirements on labor force for optical fiber production, concerning as well number as qualification, are suprisingly low. For a reference plant the estimate of the total number of employees is 60 to 100 persons /27/. This is true for actual, well-running production; in the initial starting-up phase and, also, for the R&D activities going on in parallel to production highly qualified specialists are needed. In addition, craftsmen like electrician, plumbers, glass-blowers, further managers, accountants, typing clerks will be needed. At least one chemical, electronic (control), optical, and communications engineer each should also belong to the production staff. Training of workers is usually done on the job. Senior workers train their younger or new colleagues. In USA and Japan, a majority of the semi-skilled workers are high school graduates.

6.7 Storage capacity

The toughest storage requirement is presented by the pure gases. Not only are large amounts needed but some of the gases are toxic and some are inflammable. $SiCl_4$ and $GeCl_4$ are liquids that come in specially sealed cylinders, at pressures near atmospheric. Oxygen supports immediate combustion of almost any substance and is particularly incompatible with hydrocarbons. It should be therefore kept outside the factory in a safe place. Hydrogen is highly flammable in air, so storage outside the plant buildings is mandatory.

The silica substrate tubes should also be carefully stored, in a dry and clean place and a manner that precludes breakage and deformation. The finished product, the optical fiber, is wound on spools (diameter 20 - 50 cm and comparable height) and stored until sold. One spool carries between 1 and 10 km of fiber, so that the required space is small compared with conventional copper cables. The spools must also be stored in dry and clean places.

6.8 Transport

For the delivery of raw materials and the shipping of the fiber, a production plant should be easily accessible. However, this requirement is not too stringent because only modest masses have to be transported. In contrast to conventional telecommunication copper wires, the transport problem is small.

7. POSITION OF DEVELOPING COUNTRIES

The central issue of this chapter is the discussion of advantages and disadvantages of DCs to fulfill the necessary requirements for fiber and cable production.

7.1 Material and energy inputs

Fiber production is not restricted to special locations as a consequence of some special natural resources needed. Most of the material inputs can be produced everywhere and those which cannot be produced everywhere (pure silica tubes, germanium) must be imported from abroad in the same way as already existent fiber producers do. The real problems for DCs come a) from the fact that very high and special quality standards for these inputs must be met, and b) from economic considerations concerning the cost of raw material inputs. Fiber production requires substantial amounts of H_2, O_2 of technical purity, O_2 of very high purity as well as minor amounts of other chemicals of very high purity. Efficient fiber production can only be maintained if these inputs are continuously available, which spells a disadvantage for DCs. The main reasons for this disadvantage are economies of scale in chemical industry and higher transportation costs if there is no domestic chemical industry. It is therefore concluded that material costs will be higher in DCs than in industrialized countries.

Electrical energy again must be continuously supplied to guarantee efficient production and safety in the production facility.

7.2 Manpower requirements

There can be no doubt that in the case of a threshold country it is perfectly possible to recruit the required personnel. But one has to expect at least the following problems: higher training costs due to longer training times required, higher fluctuation costs, lower productivity. These problems become more important if one considers DCs which have not yet reached the level of threshold countries. In many DCs it will simply not be possible to recruit the necessary number of skilled and semiskilled workers to start and maintain production.

These disadvantages are counteracted by the comparably low level of wages and wage by-costs in the DCs. Since the wage bill does only account for 30% of average cost of fiber production, low wages and wage by-costs are only of limited importance for a capital intensive production as fiber production in fact is.

7.3 Capital equipment, technology transfer, research and development

Technological knowledge, patents etc. are in the hands of a few companies. Therefore it is evident that any effort directed towards optical fiber production must rely on a complete technology transfer or at least on very intensive technological cooperation with one of the leading firms in the markets. The concrete disadvantages of DCs under such an arrangement would be:

- higher production costs (royalties: 5 - 7% of gross revenue)
- technological inflexibility
- high dependency on licenser or international companies owning the facility
- reduced domestic value added and tax revenues.

Since fiberoptics is a rapidly changing technology, R&D plays an important role. If continuous R&D is not performed in the DC, a high degree of dependence on foreign companies is unavoidable. Inland R&D reduces foreign influence, but raises - in the short run - overhead costs with only minor effects on production. In the long run, however, positive effects for the DC can be expected.

7.4 General production and market conditions

Whereas DCs with adequate industrial experience are not expected to have severe disadvantages in fulfilling the special requirements on the fiber factory, somewhat different is the situation with regards to market conditions. Despite some installations in some DCs there is not yet a substantial domestic market for fiberoptics in these countries. The great bulk of produced optical fiber is deployed in industrialized countries. Many leading optical fiber producers recently expanded their production capacity to meet demand requirements in the near future. If DCs want to participate in the dynamic development of the fiberoptic markets even in their own countries strong effects must be made to be present as suppliers in time. These efforts might be contracted by at least two factors. Domestic markets in DCs tend to be small, so that fiber must be sold on the international markets. Due to the behavior of national telecommunication authorities or their private counterparts these markets are almost closed. Therefore it appears to be very tough to penetrate these markets without the assistance of an international company.

A fairly good chance to enter the fiberoptic market is to adapt an already existing copper cable plant for the cabling of optical fibers which have to be bought from foreign fiber producers. This way offers the possibility to serve - at low investment costs - the domestic demand wheredomestic suppliers have advantages because of their familiarity with the general conditions in the telecommunications sector and the national telecommunications authorities of their country.

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