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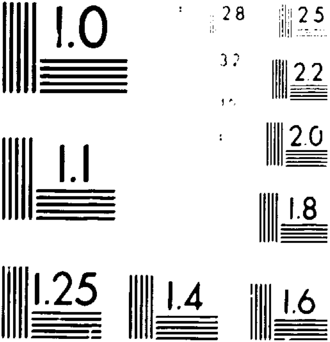

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OPTICAL FIBER PRODUCTION*

prepared by

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ABSTRACT

The current status of technologies for production of optical fibers and cables is reviewed in detail and trends of production and markets - and optical communications in general - identified.

Specific requirements are availability of pure gases and chemicals, familiarity with clean-room conditions, and qualified personnel in chemical, optical, communications and process control engineering. Capital investment for setting up a completely new fiber production unit is in the range of 10 to 20 million US dollars, R & D not included. 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, the strategy of joint venture is described as a viable one for entering the optical fiber/cable market. For least developed countries, the import of a complete new production plant is the easiest way to enter this market, but, for the LDC, not a very profitable one. It is therefore only conditionally recommended.

CONTENTS

1. BASICS OF OPTICAL COMMUNICATION

1.1 Introduction

The high carrier frequency of light promises a tremendously wide bandwidth for transmitting information compared with conventional systems. As with the invention of the laser in 1960 a powerful light source emerged, research into optical communication was greatly accelerated. Unfortunately, line-of-sight transmission through the atmosphere was restricted to some kilometers by the absorption of light due to dust, fog and rain. On the other hand, guided transmission of light through fibers was unattractive at that time, since fiber losses were still very high - more than 1000 dB/km /Kao and Hockham 1966/. The breakthrough came in 1970, when Corning Glass Works announced the development of optical fibers with losses of less than 20 dB/km /Kapron et al. 1970/. Suddenly, long-distance telecommunications by fiber optics 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. The result was a transmission link that had certain inherent advantages over conventional copper systems in telecommunication applications, which will be discussed later. 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.

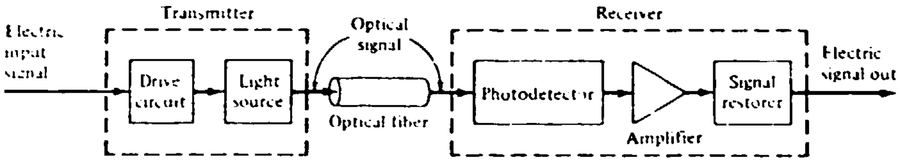

Fig.1.1: Basic elements of an optical fiber transmission link.

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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 fibers contained inside, and
- a receiver consisting of a photodetector plus amplification and signal-restoring circuitry.

Generally, the cable contains several cylindrical 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. 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.

In the following we will discuss the components of an optical fiber transmission link in more detail. We will begin with the most important component in an optical fiber system - the optical fiber itself -, since its transmission characteristics play a major role in determining the performance of the entire system. Some of the questions that arise concerning optical fibers are /Keiser 1983/:

1. What is the structure of an optical fiber?
2. How does light propagate along a fiber?
3. What is the signal loss or attenuation mechanism in a fiber?
4. Why and to what degree does a signal get distorted as it travels along a fiber?
5. Of what materials are fibers made?
6. How is the fiber fabricated?
7. How are fibers incorporated into cable structures?

The purpose of the following sections is to present some of the fundamental answers to the first four questions in order to obtain a good physical understanding of optical fibers. Questions 5 and 6 will be answered in Ch.4, whereas question 7 is addressed in Ch.5.

1.2 Optical fibers

1.2.1 Structures and waveguiding fundamentals of optical fibers

To gain insight into the nature of light propagation within a fiber waveguide, it is appropriate to start with the phenomenon of reflection and refraction at a dielectric interface. A fundamental optical parameter of a material is the refractive index n. In free space a light wave travels at a speed of $c = 3 \times 10^8$ m/s. In a dielectric material the speed of light is $v = \frac{c}{n}$, which is less than c. Whereas $n = 1.00$

for air, the value for glass is n ≈ 1.50. When a light ray encounters a boundary separating two different materials as depicted in Fig.1.2, part of the ray is reflected back, and the remainder is refracted as it enters the second material, which is a result of the difference in the speed of light in the two materials having different refractive indices.

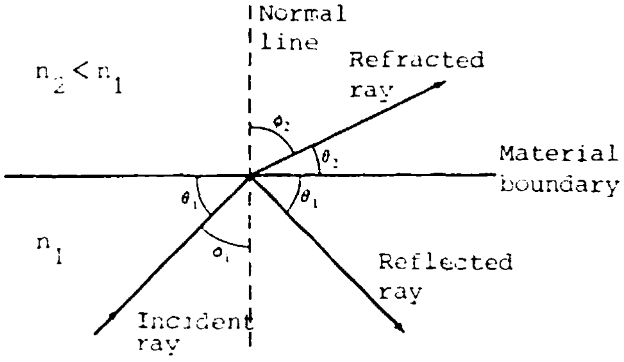

Fig.1.2: Refraction and reflection of a light ray at a material boundary.

The relationship at the interface is known as Snell's law and is given by

$$n_1 \sin\Phi_1 = n_2 \sin\Phi_2 \tag{1.1}$$

or equivalently as

$$n_1 \cos\Theta_1 = n_2 \cos\Theta_2 \tag{1.2}$$

where the angles are defined in Fig.1.2. As the angle of incidence Θ_1 in an optically denser material (higher refractive index) becomes smaller, the refracted angle Θ_2 approaches zero. The angle Θ_1, for which Θ_2 equals zero, is called the critical angle Θ_c and is easily calculated from equ.1.2 as

$$\Theta_c = \arc\cos \frac{n_2}{n_1} \; . \tag{1.3}$$

For $\Theta_1 < \Theta_c$ no refraction is possible and the light is bounded within the denser medium by total internal reflection.

Figure 1.3 illustrates the evolution of this effect.

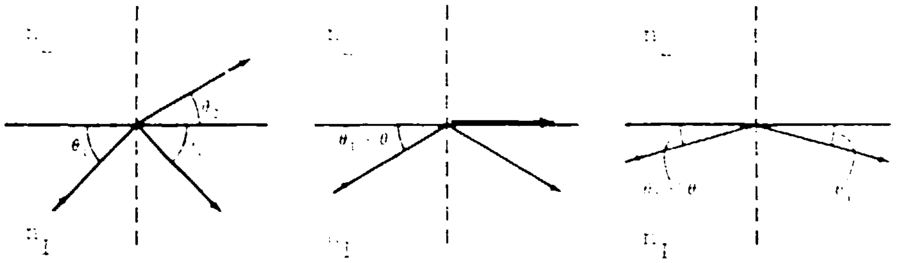

Fig.1.3: Representation of the critical angle and total internal reflection ($n_2 < n_1$).

It is exactly this effect which is the physical basis for light propagation in an optical fiber.

Now we will look at the optical fiber configurations. 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, which is usually described in terms of a set of guided electromagnetic waves called the modes of the waveguide. Each guided mode represents a pattern of electric and magnetic field lines that is repeated along the fiber at intervals equal to the wavelength. Only a certain discrete number of modes are capable of propagating along the guide depending on the fiber structure.

Although many different configurations of the optical waveguide have been discussed in the literature, the most widely accepted structure is the single solid dielectric cylinder of radius a and index of refraction n_1 shown in Fig.1.4. This cylinder is called the core of the fiber. The core is surrounded by a solid dielectric cladding having a refractive index n_2 that is less than n_1.

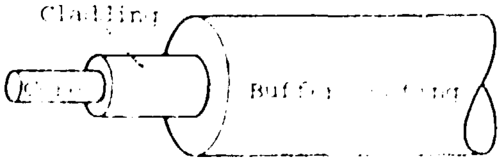

Fig.1.4: Schematic of a single-fiber structure. A circular solid core (n_1) is surrounded by a cladding having a refractive index $n_2 < n_1$. An elastic plastic buffer encapsulates the fiber.

Although air would be sufficient to provide total internal reflection, the cladding reduces scattering loss resulting from dielectric discontinuities at the core surface, it adds mechanical strength to the fiber, and it protects the core from absorbing surface contaminants. In low- and medium-loss fibers the core material is generally glass which is surrounded by either a glass or plastic cladding. Higher-loss plastic core fibers with plastic claddings are also in use. An additional encapsulation in an elastic, abrasion-resistant plastic material, called jacket, adds further strength to the fiber and mechanically isolates or buffers the fibers from small geometrical irregularities to prevent scattering loss induced by microscopic bends.

Variations of the material composition of the core give rise to the two commonly used fiber types. In the first type, the so-called step-index fiber (SI), the refractive index of the core is uniform throughout and undergoes an abrupt change (= step) at the cladding boundary, which is described by the profile function

$$n(r) = \begin{cases} n_1 & \text{for } r \leq a \\ n_1(1-\Delta) = n_2 & \text{for } r > a \end{cases} \qquad (1.4)$$

The parameter Δ is called the core-cladding index difference or simply the index difference. Typical values are $\Delta = 0.01$ and $n_1 = 1.48$. In the second case the core refractive index is made to vary gradually as a function of the radial distance from the center of the fiber. The profile function is usually given by

$$n(r) = \begin{cases} n_1 \left[1-2\Delta\left(\frac{r}{a}\right)^{\alpha}\right]^{1/2} & \text{for } r \leq a \\ n_1(1-2\Delta)^{1/2} \approx n_1(1-\Delta) = n_2 & \text{for } r > a \end{cases} \qquad (1.5)$$

Here r is the radial distance from the axis, 2a is the diameter of the core, and the dimensionless parameter α with a typical value of 2 defines the shape of the index profile. The index difference Δ for this type of fiber is given by

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \approx \frac{n_1 - n_2}{n_1} . \qquad (1.6)$$

(For $\alpha \rightarrow \infty$, Eq.1.5 reduces to the SI-profile $n(r) = n_1$ for $r \leq a$). This type is called a graded-index fiber (GI). If the structure supports only one mode of propagation (= the fundamental mode), the fiber is called a single-mode fiber (SM). Otherwise it is a multimode fiber (MM) containing many hundreds of modes. Usually, SM-fibers are of the step-index type. The condition for single-mode operation is /Wolf 1979/

$$V = \frac{2\pi a}{\lambda} (n_1^2 - n_2^2)^{1/2} \leq 2.405, \qquad (1.7)$$

which can be fulfilled by letting the dimensions of the core diameter be a few wavelengths (usually 8 to 12) and by having small (0.1 to 0.2 percent) index differences between the core and the cladding. The normalized frequency V can also be related to the number of modes M in a multimode SI-fiber where M is $M \approx V^2/2$. The total number of bound modes in a graded-index fiber is given by

$$M = \frac{\alpha}{\alpha+2} \left(\frac{2\pi a n_1}{\lambda}\right)^2 \Delta . \qquad (1.8)$$

Typical dimensions of single- and multimode fibers are given in Fig.1.5 to provide an idea of the dimensional scale.

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

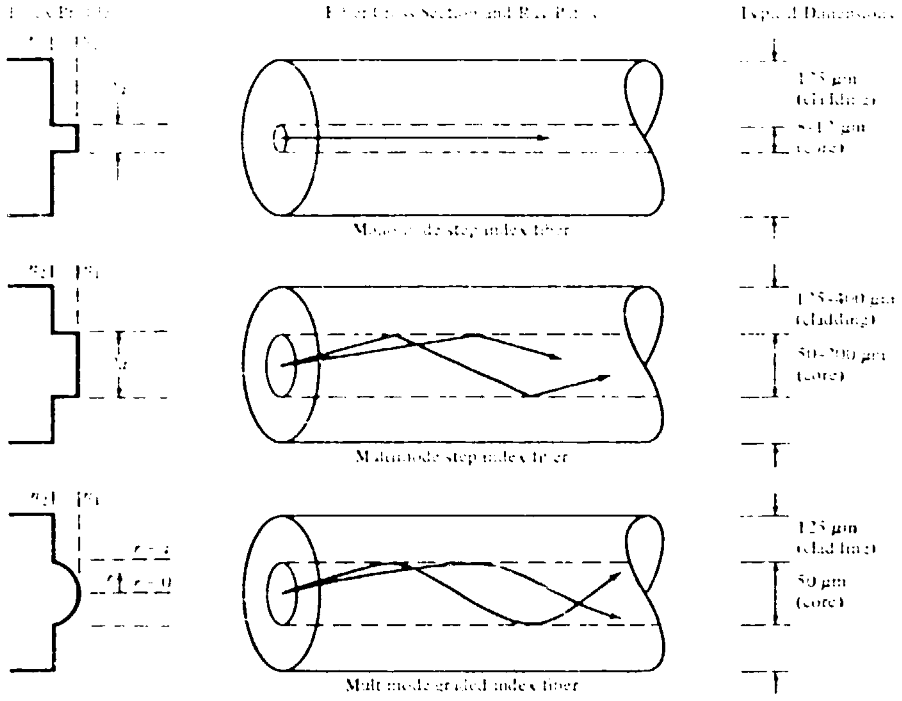

Fig.1.5: Comparison of step-index (single- and multimode) and graded-index optical fibers.

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A commonly used parameter to describe the light acceptance or gathering capability of a fiber and to calculate source-to-fiber optical power coupling efficiencies is the numerical aperture NA, a measure for the maximum acceptance angle Θ_o. Looking at Fig.1.6 one derives

$$NA = n \sin \Theta_o = (n_1^2 - n_2^2)^{1/2} \approx n_1 \sqrt{2\Delta} , \qquad (1.9)$$

which is valid for SI-fibers.

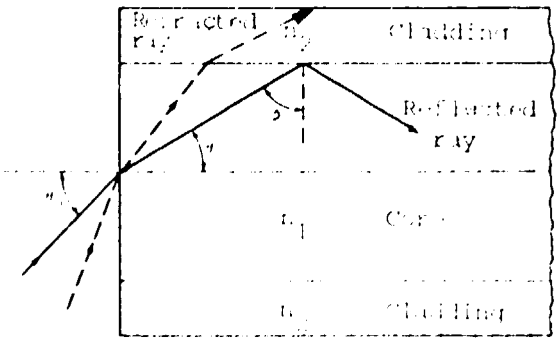

Fig.1.6: Ray optics representation of the numerical aperture in a step-index fiber.

The determination of the NA for graded-index fibers is more complex than for step-index fibers. Because of the index variation n(r) NA is a function of position across the core endface. The <u>local NA</u> is defined as

$$NA(r) = \begin{cases} [n^2(r)-n_2^2]^{1/2} \approx NA(o)\sqrt{1-(\frac{r}{a})^{\alpha}} & \text{for } r \leq a \\ 0 & \text{for } r > a \end{cases} \qquad (1.10)$$

where the <u>axial numerical aperture</u> is defined as

$$NA(0) = [n^2(0)-n_2^2]^{1/2} = (n_1^2-n_2^2)^{1/2} \approx n_1\sqrt{2\Delta}. \qquad (1.11)$$

To calculate the power coupled into a fiber one has to integrate the radiance over the solid acceptance angle of the fiber. To illustrate the influence of the NA on the coupling efficiency we refer to Fig.1.7 and give the solution of the integral, as an example, for a very simple case: A step-index fiber is centered over a surface-emitting LED of radius r_s and is positioned as close as possible.

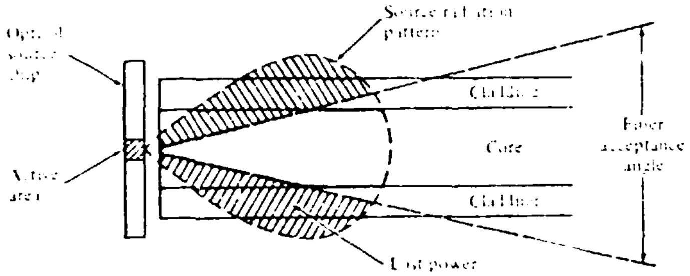

Fig.1.7: Coupling an optical source to a fiber. Light outside the acceptance angle is lost.
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The power P_F coupled into the fiber expressed in terms of the emitted power P_S is

$$P_F = P_S(NA)^2 \qquad \text{for } r_s \leq a. \qquad (1.12)$$

If the radius of the emitting area is larger than the core radius, Eq. (1.12) becomes

$$P_F = P_S(\frac{a}{r_s})^2(NA)^2 \qquad \text{for } r_s > a \qquad (1.13)$$

1.2.2 Signal degradation in optical fibers

1.2.2.1. Signal attenuation

Signal attenuation (also known as fiber loss or signal loss) is one of the most important properties of an optical fiber, because it largely determines the maximum repeaterless separation between a transmitter and a receiver. Since repeaters are expensive to fabricate, install, and maintain, the degree of attenuation in a fiber has a large influence on system cost. Signal attenuation is defined as the ratio of the optical output power P_{out} from a fiber of length L to the optical input power P_{in}. The symbol α_L is used to express attenuation in decibels per kilometer

$$\alpha_L = 10 \log \frac{P_{in}/P_{out}}{L} . \qquad (1.14)$$

If an actual fiber has a 3 dB/km-loss, for instance, the optical signal power would decrease by 50 percent over a 1 km length.

The intrinsic loss of high silica glasses in the near infrared region of the spectrum is composed of ultraviolet absorption, infrared absorption and Rayleigh scattering. Ultraviolet absorption is determined by the electronic bandgap of a material and decays exponentially with increasing wavelength. The tail of the UV edge in glasses is almost negligibly small in the near infrared. The loss increase above 1600 nm is caused by the infrared absorption tail resulting from very strong cation-oxygen vibrational modes of the glass lattice at long wavelengths. Rayleigh scattering α_R results from compositional and density fluctuations of the glass over distances much smaller than the wavelength of light. Microscopic density variations give rise to small index variations which are the reason for the existence of the same phenomenon in fibers that scatters light from the sun in the atmosphere, thereby giving rise to a blue sky. This loss distribution decays with the fourth power of wavelength, as expressed by $\alpha_R = A_R \lambda^{-4}$ -shown in Fig.1.8-, and gives the attenuation-versus-wavelength curves their characteristic downward trend with increasing wavelength. A_R is the Rayleigh scattering coefficient, which depends on the nature of the dopant and its concentration. In general, the higher the Δ of the fiber, typically accomplished by increasing GeO_2 levels, the higher the intrinsic loss levels /Nagel et al. 1982/.

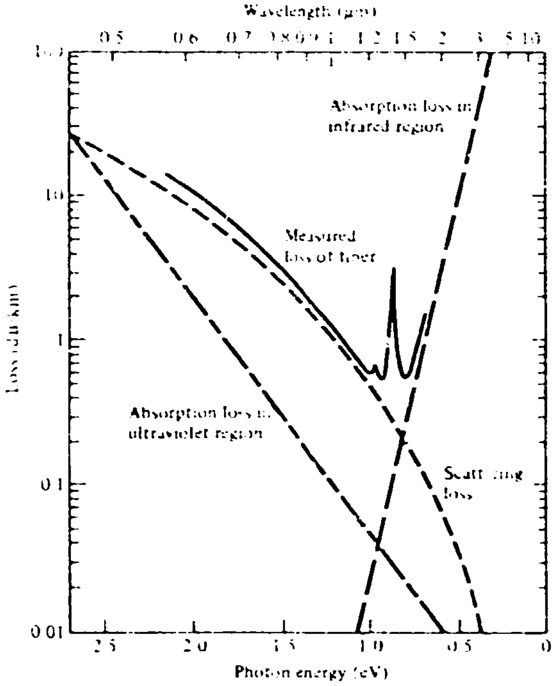

Fig.1.8: Optical fiber attenuation characteristics and their limiting mechanisms for a GeO_2-doped low-loss low-OH-content fiber /Osanai et.al.1976/; reproduced with permission.

Extrinsic loss mechanism due to impurities, imperfections, and fiber design in regard to bend sensitivity can cause additional attenuation. Transition metal ions (Fe,Cr,Cu) at the level of a few ppb's can cause unacceptably high absorption losses in lightguides. Another source of absorption is due to hydroxyl ions (OH) in the glass structure. In silica-based glasses, a strong fundamental Si-OH vibration occurs at ~2.7 μm and results in a first and second overtone at 1.38 and 0.95 μm, respectively, and a combination overtone at 1.25 μm. For every ppm OH, losses of 48 dB/km at 1.38 μm, 2.5 dB/km at 1.25 μm, and 1.2 dB/km at 0.95 μm are added; thus, very low levels of OH are necessary to achieve low loss at long wavelengths, especially because the peaks are relatively broad. The exact peak position and width are a function of composition, with additions of GeO_2 moving the peak to longer wavelengths. Figure 1.9 shows the large absorption peaks at 950, 1250 and 1380 nm caused by high levels of OH ions in early optical fibers.

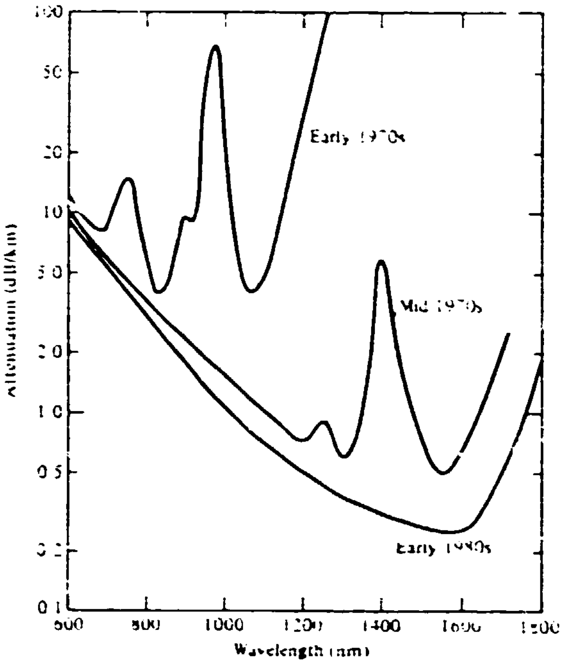

Fig.1.9: Optical fiber attenuation as a function of wavelength. Material research and improved fabrication methods reduced the attenuation especially at longer wavelengths.

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The peaks and valleys in the attenuation curve resulted in the assignment of various "transmission windows" to early optical fibers. Significant progress has been made in reducing the residual OH content to fibers to less than 1 ppb /Chida et al. 1982a/.The resulting loss curve (lowest curve in Fig.1.9) exhibits no more peaks and an absorption minimum of 0.2 dB/km at 1550 nm.

Radiative losses occur whenever a fiber undergoes a bend of finite radius of curvature. Large-curvature radiation losses occuring if a fiber cable turns a corner can be understood by the fact that the tail of the field distribution of the optical mode on the far side of the center of curvature must move faster to keep up with the field in the core. At a certain distance from the center the field tail would have to move faster than the speed of light which is not possible - so the optical energy in the field tail radiates away. Another form of radiation loss results from mode coupling caused by random microbends of the optical fiber /Gardener 1975/, which are repetitive changes in the radius of curvature of the fiber axis, as is illustrated in Fig.1.10.

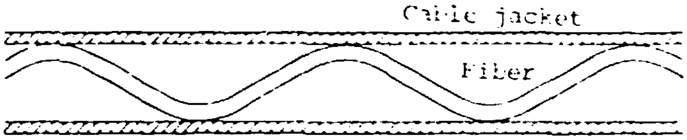

Fig.1.10: Microbends shown as repetitive changes in the radius of curvature of the fiber axis.

They are caused either by nonuniformities in the sheathing of the fiber or by nonuniform lateral pressures created during the cabling of the fiber. The latter effect is often referred to as cabling or packaging loss.

1.2.2.2 Signal distortion

An optical signal becomes increasingly distorted as it travels along a fiber. As Fig.1.11 shows, the distortion causes optical signal pulses to broaden and to overlap with neighboring pulses, thereby creating errors in the receiver output. The signal distorsion mechanisms thus limit the information-carrying capacity of a fiber.

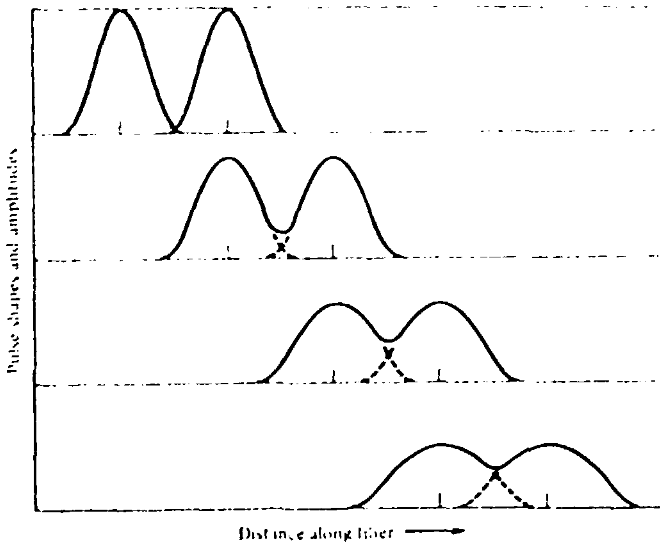

Fig.1.11: Broadening and attenuation of two adjacent pulses as they travel along a fiber

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Two types of distorsion effects can be distinguished. Intramodal (= chromatic) dispersion is pulse spreading that occurs within a single mode. It is a result of the dependence of the group velocity on wavelength λ. Due to its wavelength dependence intramodal dispersion increases with the spectral width of the optical source. The main causes of intramodal dispersion are material dispersion, which arises from the variation of the refractive index of the core material as a function of wavelength, and waveguide dispersion, which occurs because the modal propagation constant is a function of the ratio core radius to wavelength a/λ. Intramodal dispersion is usually measured in ps/(nm.km).

The other factor giving rise to pulse spreading is intermodal dispersion which is a result of the fact that in a multimode waveguide each mode is traveling at a different velocity. The higher the mode number, the slower is the axial group velocity. This variation in the group velocity of the different modes results in a group delay spread or intermodal dispersion. This distorsion mechanism is eliminated by single-mode operation, but it is important in MM-step-index fibers, where it dominates by an order of magnitude the other two dispersion effects. This dominating influence can be greatly reduced by a carefully designed nearly parabolic graded-index profile. The feature of this grading is that it offers multimode propagation in a relatively large core together with the possibility of very low intermodal delay distortion /Keiser 1983/. This combination allows the transmission of high data rates over long distances while still maintaining a reasonable degree of light launching and coupling ease. Figure 1.12 demonstrates the influence of the exact value of the index gradient α on the pulse spreading and the effect of the spectral width of the source. The calculated transmission capacities are 0.13, 2, and 10 (Gbit/s)km. Although theory predicts a sharp minimum of dispersion for the exact value

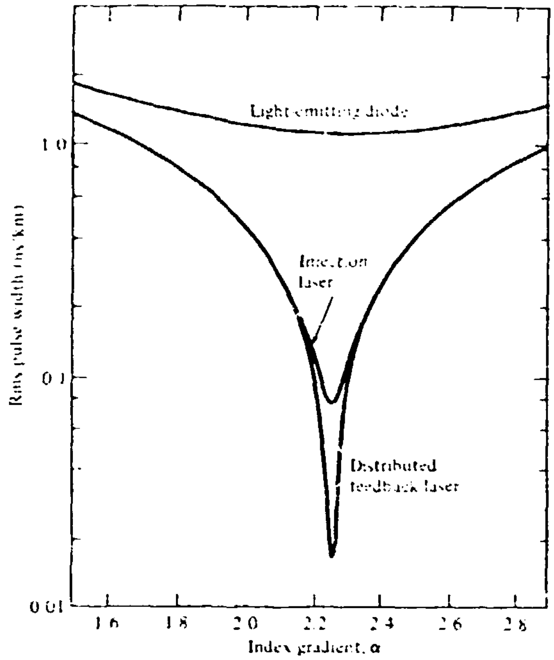

Fig.1.12: Pulse spreading in a GI-fiber versus the index parameter α at $\lambda = 900$ nm. Material dispersion is included for an LED, and ILD, and a distributed-feedback laser having spectral widths of 15, 1, and 0.2 nm, respectively /Olshansky and Keck 1976/; reproduced with permission.

of α, in practice unavoidable manufacturing tolerances cause slight deviations of the index profile from its optimum shape decreasing the fiber bandwidth dramatically. Unfortunately, the value of α which minimizes pulse distortion depends strongly on wavelength, because each refractive index value of the graded-index profile has a different variation with wavelength due to the different material composition. This effect is called profile dispersion.

Of these effects, waveguide dispersion usually can be ignored in multimode fibers. However, it plays an important role for SM-fibers. Material dispersion is of particular importance for single-mode waveguides and for LED systems, since a LED has a broader spectrum than a laser diode. An interesting feature of silica partly responsible for the recent R & D-activities in the wavelength region around $\lambda = 1.3$ µm is the fact, that material dispersion goes through zero at this wavelength. Fig.1.13 shows that in single-mode fibers the total dispersion can be reduced to zero at a particular wavelength in the 1.3 to 1.7 µm range by the mutual cancellation of material and waveguide dispersions /Jeunhomme 1979/. For GeO_2-doped fibers this is achieved by varying the amount of GeO_2 dopant to obtain different material behaviour, and by controlling the waveguide effects through variations in core diameter and core-cladding index difference.

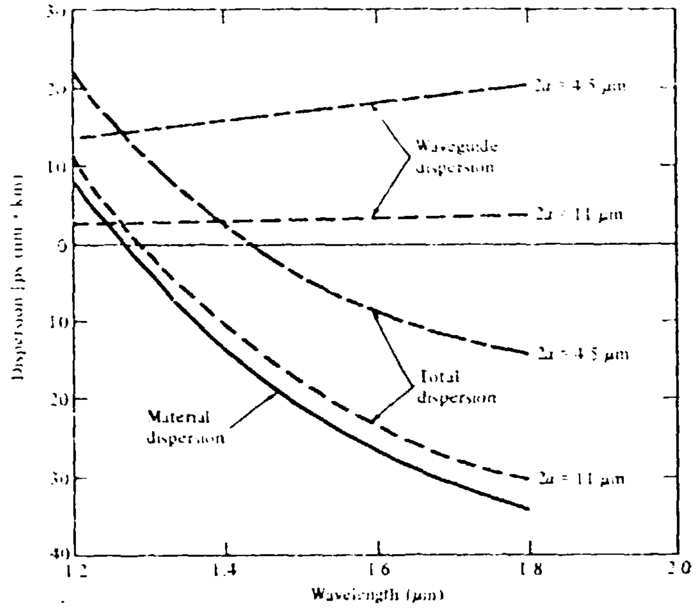

Fig.1.13: Example for the mutual cancellation of material and waveguide dispersion in a SM-fiber by changing the waveguide dimensions.

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The total pulse broadening σ in a fiber can be obtained from the sum

$$\sigma = (\sum_i \sigma_i^2)^{\frac{1}{2}} , \qquad (1.15)$$

where σ_i stands for the various dispersion effects. The equivalent characterization in the frequency domain recommended by CCITT is given by the baseband response

$$B = (\sum_i B_i^2)^{-\frac{1}{2}} \qquad (1.16)$$

where B_i are the bandwidths corresponding to the various dispersion effects /CCITT COM XV-R 39E 1983/. Pulse broadening and baseband response are connected via the Fourier transformation.

A measure of the information capacity of an optical waveguide is usually specified by the bandwidth-distance product in MHz.km, where the bandwidth is defined as the frequency at which the power transfer function has fallen to one-half the value of the zero frequency value (3 dB). For a step-index fiber the various distortion effects tend to limit the bandwidth-distance product to about 20 MHz.km. Graded-index fibers exhibit a value as high as 2.5 GHz.km. Single-mode fibers can have capacities well in excess of this.

In real systems pulse distortion does not depend with 1/L of the fiber length L, but will increase less rapidly after a certain initial length of fiber because of mode coupling and differential mode loss. In this initial length of fiber, coupling of energy from one mode to another arises because of structural imperfections, diameter and index variations, and cabling-induced microbends. The mode coupling tends to average out the propagation delays associated with the modes, thereby changing the intermodal dispersion from an 1/L dependence to a $1/\sqrt{L}$ dependence (see Fig.1.14). From practical field experience it has been found that the bandwidth B in a link of length L can be expressed by the empirical relation

$$B(L) = \frac{B_o}{L^q} \qquad (1.17)$$

where B_o is the bandwidth of a 1-km length of cable, and the concatenation factor q ranges between $q = 0.5$ (steady-state modal equilibrium) and $q = 1$ (little mode mixing) /Keiser 1983/.

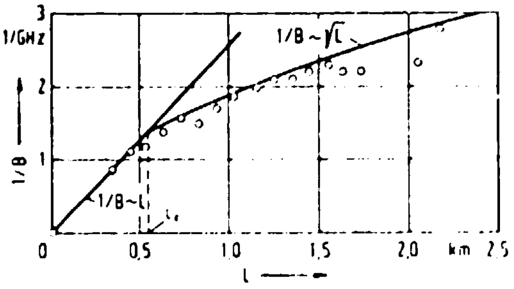


Fig.1.14: Transmission bandwidth of a graded-index fiber versus fiber length, o are experimental data /Kersten 1983/; reproduced with permission.

1.3 Light sources for optical fiber links

In this section we will briefly discuss the principal light sources used for fiber optic communication, which are heterojunction-structured semiconductor injection laser diodes (ILD) and light-emitting diodes (LED). These devices are suitable for fiber transmission systems because they have adequate output power, their optical output power 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. Here, we can give only an overview of the pertinent characteristics, a comprehensive treatment of LEDs and IDLs is presented in / Kressel 1982/.

The light-emitting region of both LEDs and ILDs consists of a pn junction constructed of direct-band-gap III-V semiconductor materials. When this junction is forward-biased, electrons and holes are injected into the p and n regions, respectively. If the injected minority carriers recombine radiatively, a photon of energy equal the bandgap is emitted. This pn junction is called the active or recombination region. As the bandgap determines the emission wavelength, ternary and quaternary alloys are used to cover a broad range of emission wavelengths. In the 800 to 900 nm region the light sources are generally alloys of GaAlAs. At the longer wavelengths (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. The optical energy released from the optical resonant cavity of a laser diode has spatial and temporal coherence, which means it is highly mo- monochromatic ($\Delta\lambda < 2$ nm) and that the output beam is very directional. Since a LED has no wavelength selective cavity its optical radiation has a broad spectral width ($\approx 5\%$ of central wavelength). In addition, the incoherent energy is emitted into a hemisphere according to a cosine power distribution and, thus, has a large beam divergence (see Fig. 1.15)

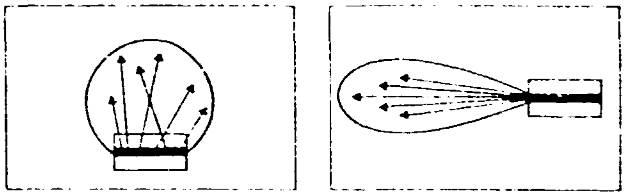


Fig. 1.15: Radiating characteristics of a LED (left) and an injection laser (right). Telefunken electronic GmbH, Heilbronn, West Germany, reproduced with permission.

Because of its higher output power of up to 40 mW /Kressel 1982/ and its monochromatic emission, the injection laser is best suited for long-distance transmission. Along with this major advantage some disadvantages have to be mentioned. Cost is much higher for lasers than for LEDs. Lasers are extremely sensitive to temperature requiring a feedback control to maintain the output power constant. In early days, lifetime of lasers at room temperature was much less than that of LEDs, but, nowadays, this is no longer a problem, as lifetimes of more than 10^6 hours are predicted /Kressel 1982/. With laser diodes higher modulation rates are possible due to a faster response time. As Fig. 1.16 demonstrates, ILDs exhibit a nonlinear light/current-characteristic with a typical threshold current, so that digital

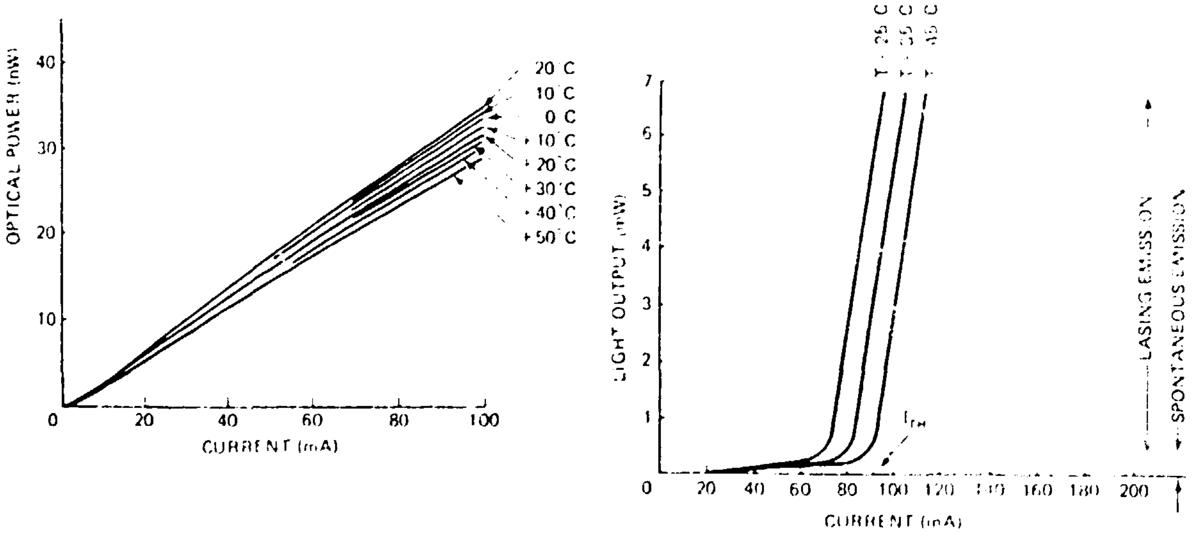


Fig. 1.16: Power vs. current characteristics for a typical LED (a) and a laser diode (b). Temperature is a parameter. Reprinted with permission from Electronic Design, Vol.28, No.8; copyright Hayden Publishing Co., Inc., 1980.

modulation is the preferred modulation format with ILDs. Modulation up to some Gbit/s has been reported /Kressel 1982/. The LED exhibits nearly a linear relationship between current input and light output which makes a LED ideally suited for transmitting analog signals (especially is this true for short distances and low modulation rates <50 MHz).

Two basic LED configurations are given in Fig. 1.17. In the surface emitter or Burrus type the plane of the active light-emitting region is oriented perpendicularly to the axis of the fiber. A short length of fiber (< 1 m) is cemented into an etched well, forming a so-called "pigtail". Once installed, the pigtail allows fiber-to-fiber splicing which can be simpler than aligning the fiber end to the tiny light spot on the LED. The construction of the edge emitter is similar to a laser diode.

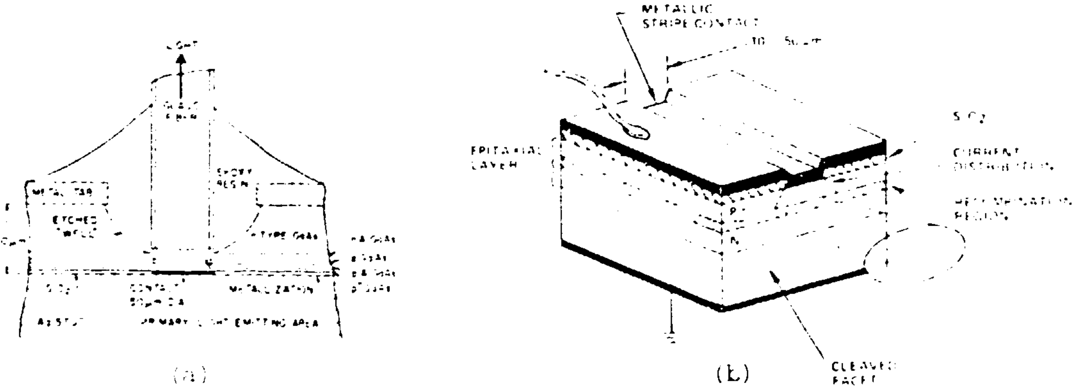


Fig. 1.17: LED configurations:
(a) Burrus-type or surface emitter with fiber pigtail /Lee 1982/; reproduced with permission.
(b) Edge emitter; RCA Corp., Lancaster, PA, USA, reproduced with permission.

Although LEDs with output powers up to 5 mW and bandwidths of 200 MHz are now available in the 0.9 and 1.3 µm region, respectively /Lee 1982/, it is the poor power coupling efficiency of LEDs which gives an advantage for laser diodes, if long distances have to be bridged. Fig. 1.18 demonstrates this drastically.

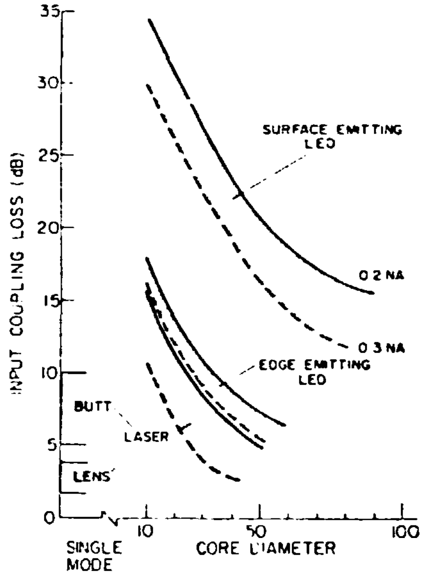
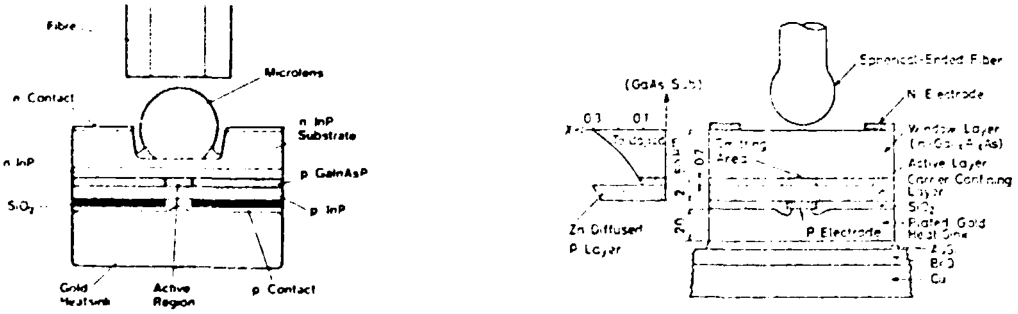


Fig. 1.18: Input coupling loss dependence as a function of fiber core diameter for three types of semiconductor sources. The solid and dashed lines bounding the shaded regions indicate the performance for 0.2 and 0.3 NA fibers, respectively /Keck 1982/; reproduced with permission.

Two methods to improve coupling efficiency are given in Fig. 1.19 /Lee 1982/.



(a)

(b)

Fig. 1.19: LED-to-fiber coupling:
(a) using a truncated microlens. Coupling efficiency improved by a factor of 3 to 13 compared to butt-joined fiber.
(b) using a spherical-ended fiber. Coupling efficiency improved by a factor of two /Lee 1982/, reproduced with permission.

1.4 Light detectors for optical receivers

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).

When light having photon energies exceeding the band gap energy of the semiconductor material is incident on a photodetector, the photons can give up their energy and excite electrons from the valence band to the conduction band. This process generates free electron-hole pairs, which are known as photocarriers. When a reverse-bias voltage is applied across the photodetector, the resultant electric field in the device causes the carriers to separate. This gives rise to a current flow in an external circuit, which is known as the photocurrent. Avalanche photodiodes internally multiply the primary signal photocurrent by impact ionization in a high-electric-field region. This increases receiver sensitivity since the photocurrent is multiplied before encountering the thermal noise associated with the receiver circuit. Typical gain for Si-APDs is 200. A stabilized high DC voltage of typically 180 V is necessary, which is a disadvantage of the APD compared to the pin photodiode. The latter can also provide faster pulse response (35 ps risetime /Optoelectronic 1983/). Ge-APDs exhibit only moderate avalanche gains of 10 to 30.

Important detector performance parameters are the quantum efficiency, which is defined as the number of electron-hole carrier pairs generated per incident photon (typically 30 to 95%), and the responsivity, which specifies the photocurrent generated per unit optical power.

Fig. 1.20 compares the quantum efficiency and responsivity for Si, Ge, and InGaAs.

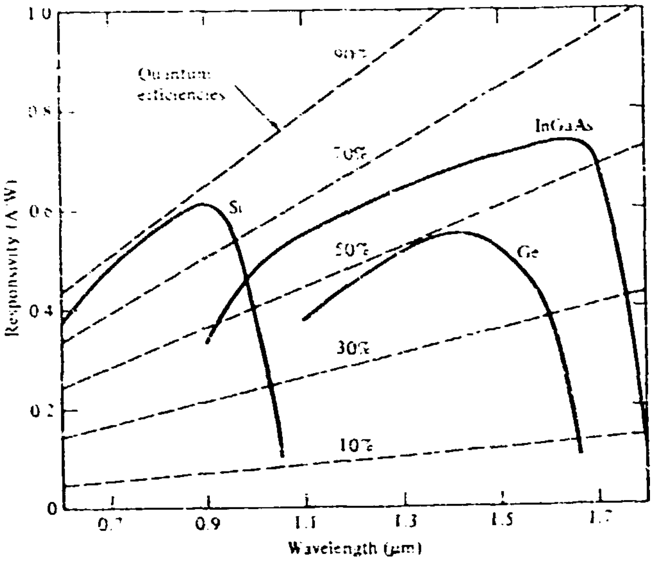


Fig. 1.20: Comparison of the responsivity and quantum efficiency as a function of wavelength for pin photodiodes constructed of different materials.

Reproduced with permission: G.Keiser, Optical Fiber Communications, McGraw Hill, 1983.

This comparison clearly reveals that silicon is the main material used for the 800 to 900 nm region (first window). For wavelengths above 1000 nm the responsivity of Si is too low. Photodiodes exhibiting high quantum efficiency and fast response time for the 1.0 to 1.65 µm region (2. and 3. window) have been made from various materials, in particular Ge and InGaAs. As an alternative to the poor avalanche gain of these materials photomodules have been developed, where a hybrid low-noise FET preamplifier on the same chip provides high sensitivity / RCA 1983/.

Figure 1.21 compares the performance of commonly used detector types for the 0.9 and 1.3 µm region.

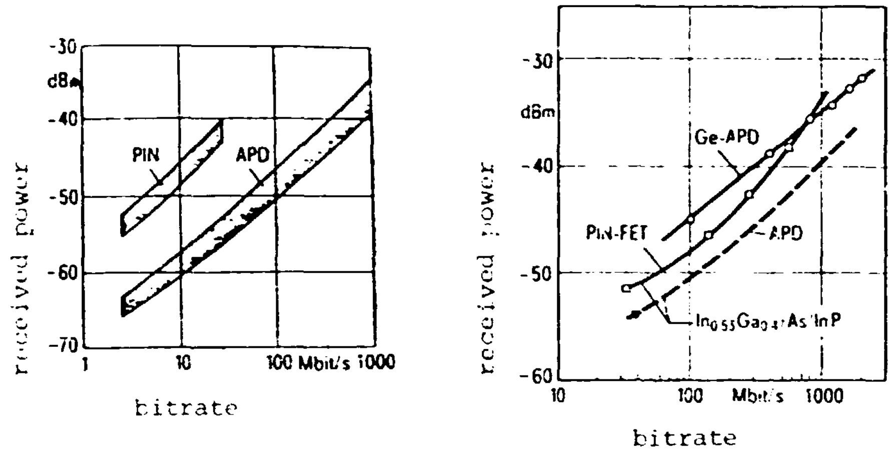


Fig. 1.21: Required power at the receiver to obtain a bit-error-rate (BER) of 10^{-9} for
(a) Si-photodiodes for 0.8 to 0.9 µm.
(b) Ge-APD and InGaAs/InP-photodiodes (PIN-FET hybrid combination and APD) /Plihal 1983/, reproduced with permission.

1.5 Comparison with conventional telecommunications

Now we will present the advantages of fiber optic transmission compared with conventional electrical telecommunication (twisted wire pair, coaxial cable, microwaves) /Lacy 1982/.

- An extremely wide bandwidth and a very low attenuation means that a greater volume of information or messages or conversations can be carried over a particular transmission line. Figure 1.22 compares the attenuation of optical fibers with copper wires and coaxial tubes.

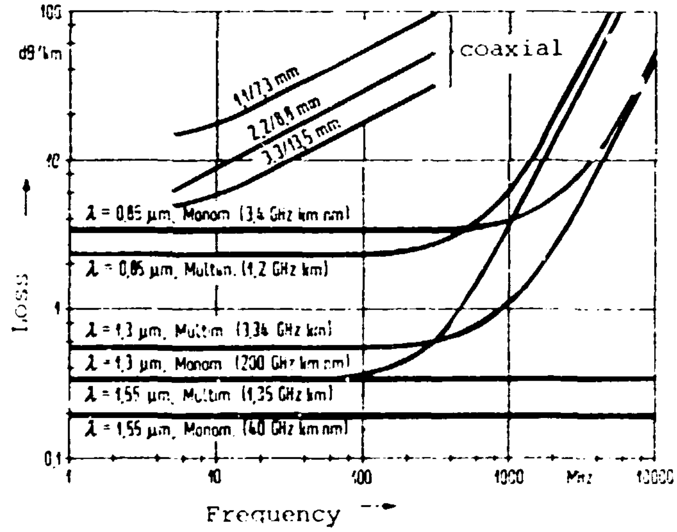


Fig.1.22: Transmission performance of optical fibers compared with copper cables (attenuation/km vs frequency) /Grau 1981/, reproduced with permission.

The attenuation of coaxial cables increases continuously with $f^{1/2}$ which requires repeaters in distances of a few kilometers with expensive electronic circuitries to reshape the distorted signals. In comparison the attenuation curve of fibers is flat up to the dispersion-determined bandwidth limit. With such bandwidths it is possible to transmit thousands of voice conversations or dozens of video signals over the same fiber over some ten of kilometers without repeaters. Transmission rates up to 10 Gbit/s seem possible which can be multiplied by wavelength-division-multiplex.

- Small-diameter, lighter-weight cables are obvious advantages with the hair-thin fibers. For example, a 0.125 mm diameter optical fiber in a jacket about 6.3 mm in diameter can replace a 76 mm bundle of 900 pairs of copper wire. The enormous size reduction (easily 10:1) allows fiber-optic cables to be threaded into crowded underground conduits or ducts without digging up city streets to lay new conduits. Together with the size reduction goes an enormous reduction in weight (25:1), which is an important advantage in aircraft, satellites and space vehicles, ships, high-rise buildings. It leads also to cost savings in transportation, storage and installation.

- In conventional communication circuits, signals often stray from one circuit to another, resulting in other calls being heard in the background. This crosstalk is negligible with fiber optics even when numerous fibers are cabled together. Greater security through almost total immunity to wiretapping is a matter of much greater importance to military services, banks, and computer networks than it is to the average citizen who is calling a relative thousands of miles away. But for these groups, communication security, that is, telephone or data privacy, is well worth any increased cost. Unless a steel cable is added to a fiber-optic cable for strength, a fiber cable can be laid in an undetectable fashion. It just cannot be found with metal detectors or electromagnetic flux measurement equipment as is the case with wire pairs and coax. As the light in an optical fiber does not radiate outside the cable, the only way to eavesdrop is to couple a tap directly into the fiber. If an eavesdropper were smart enough to do this, he or she could force some light (and therefore the message) out, but the loss would be so great at the receiving end that an alarm would be sounded. When that happens, one can measure the distance to the tap within a few inches by using time-domain reflectometers.

- Immunity to inductive interference. As dielectrics, rather than metal, optical fibers do not act as antennas to pick up radio-frequency interference (RFI), electromagnetic interference (EMI), or electromagnetic pulses (EMP). The result is noise-free transmission. That is, fiber-optic cables are immune to interference caused by lightning, nearby electric motors, relays, and dozens of other electrical noise generators which induce problems on copper cables unless shielded and filtered. Carrying light rather than electrical signals, fiber-optic cables ignore these electrical disturbances. Thus, they can operate readily in a noise electrical environment. They are particularly useful in nuclear environments because of their immunity of EMP effects. Because of their immunity to electromagnetic fields, fiber-optic cables do not require bulky metal shielding and can be run in the same cable trays as power cabling if necessary.

- Greater safety is available with fiber optics because only light, not electricity, is being conducted. Thus, if a fiber-optic cable is damaged, there is no spark from a short circuit. Consequently, fiber-optic cables can be routed through areas (such as chemical plants and coal mines) with highly volatile gases without fear of causing fire or explosion. In effect, as long as the fiber-optic cable does not have a steel strength member it provides electrical isolation between the transmitter and the receiver. If a cable is disrupted, there can be no short circuit-loading reflections back to the terminal equipment. In addition, there is no shock hazard with fiber-optic cables. Fibers can be repaired in the field even when the equipment is turned on.

- Because fiber-optic cables are made of glass or plastic, in contrast to metal, they have high tolerance to temperature extremes as well as to liquids and corrosive gases.

- A longer life span is predicted for fiber optics: 20 to 30 years, compared to 12 to 15 years for conventional cable. Glass, after all, does not corrode as metal does, and does not change its performance characteristics provided that hydrogen permeation is prohibited by an inpermeable jacket /Kuwazuru et al. 1984/.

- Potential of delivering signals at a lower cost. Sand, the basic ingredient of glass optical fibers, and plastic are of course cheaper than copper. However, because of the ultrapurity needed and the relatively low volume of production at present, individual fibers cost $ 0.30 to $ 1.50 a meter,compared with about $ 0.02 a meter for a pair of copper wires /Bylinsky 1980/. As fiber-optic systems become more common, the price is expected to drop significantly. But for now, designers must closely examine the cost-to-benefit ratio. In very short-haul applications, it is difficult for fiber optics to compete economically with copper wires. However, where the communication capacity would require coax rather than copper wires, or where interference would require special shielding for metallic wire, fiber links can be competitive even at today's prices. Lifetime costs for a fiber-optic system may be much more attractive and a better basis for comparing fiber optics with wire pairs or coax. Such costs include shipping, handling, and installation as well as manufacture. Before the cable is installed, shipping and handling costs are about one-fourth that the current metal cable and labor for installation is about one-half less. Still another cost saver is that connectors used with copper cable are usually gold-plated, whereas fiber optic connectors are made from nylon and plastic. Because of low line losses, fewer line amplifiers (repeaters) are needed for fiber optics.

2. TECHNOLOGY TRENDS

In this chapter we will discuss the trends in telecommunications systems as far as fiberoptics are concerned. General trends to be observed are

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

Starting from the present status of fiberoptics we will focus on technologically possible developments and implementations. Therefore we refer to work which is done now in numerous research laboratories around the world pointing in the direction of applications in future communications systems. For clarity's sake we catagorize the tasks for communications systems as following (refer to Fig.2.1):

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

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. In the following we will look in more detail on the possible applications indicated in Fig.2.1 and work out the direction of future development.

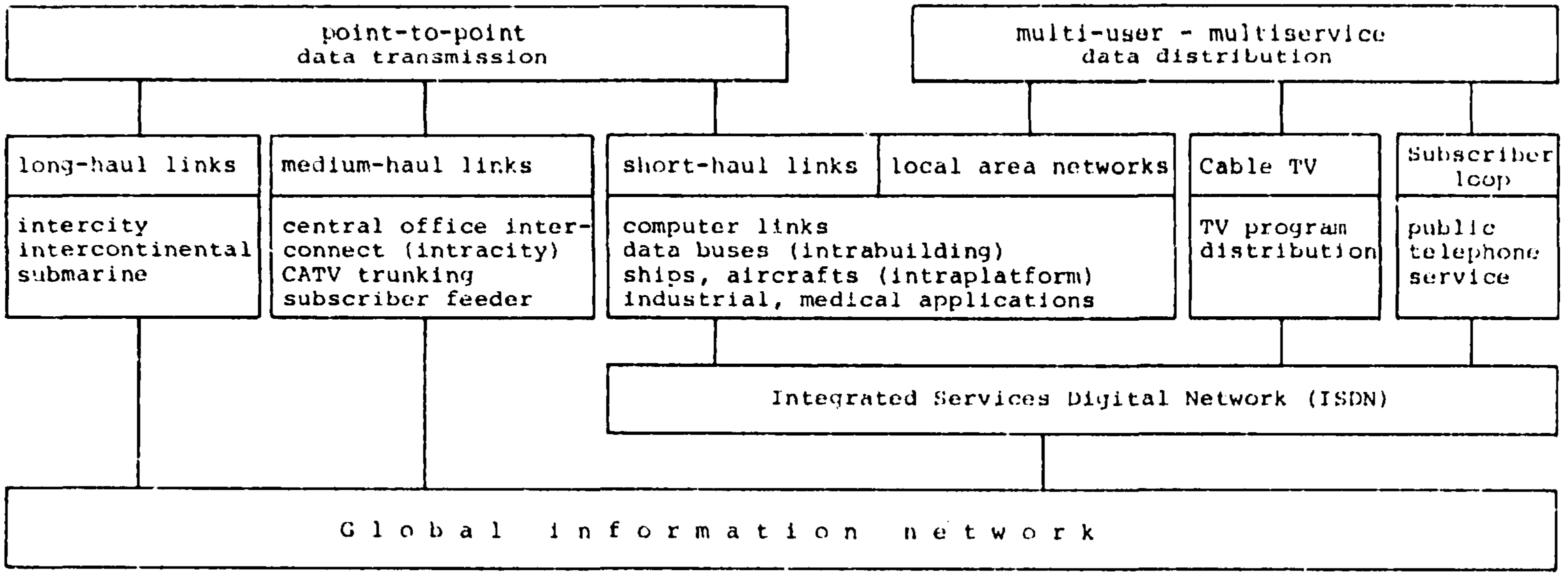


Fig.2.1: Classification of tasks in telecommunications

2.1 Transmission systems

2.1.1 Long-haul trunk lines

Long-haul trunk lines serve traffic between continents (terrestrial, submarine), islands, and cities (internationally or nationwide). The distance to be bridged ranges therefore from tens of km up to thousands of km. From the standpoint of system reliability and cost for maintenance and installation the main aim is to eliminate repeaters. At least, the number of repeaters necessary should be reduced to avoid their operation in so-called "manholes". The second aim is high-speed transmission in order to fully exploit the capacity of an installed fiber. These two requirements have led to strong effort in the development of high-performance single-mode fibers in the wavelength region around 1.3 µm characterized by zero-dispersion and low attenuation. Table 2.1 summarizes repeater spacings typical of today /Wolf 1983/.

Table 2.1: Present-day repeater spacings /Wolf 1983/

optical transmitter		LED		laserdiode	
repeater spacing limited by		attenuation	bandwidth	attenuation	bandwidth
graded-index fiber at 850 nm (400 MHz.km)					
bit rate (Mbit/s)	2	3 - 12 km		12 - 16 km	
	8		≈ 11 km	10 - 15 km	
	34		≈ 5 km	10 - 13 km	
graded-index fiber at 1300 nm (1300 MHz.km)					
bit rate (Mbit/s)	1.5-6			25 - 45 km	
	34		≈ 12 km	17 - 30 km	
	140		≈ 7 km		≈ 17 km
single-mode fiber at 1300 nm (20 GHz.km)					
bit rate (Mbit/s)	140			20 - 40 km	
	565			16 - 30 km	

As already shown in Fig.1.8 the absolute attenuation minimum of silica fibers doped with GeO_2 is located at 1.55 µm /Murata and Inagaki 1981/. Unfortunately the conventional step-index SM-fiber exhibits rather high dispersion at this wavelength of minimum loss. Therefore, two strategies exist for the exploitation of the 1.55 µm region for high-speed transmission:

- Use of the conventional fiber (with a dispersion minimum near 1.3 µm) at 1.55 µm, but with a single-frequency (= single longitudinal mode) laser the extremely spectral width of which avoids pulse broadening. Promising results have been reported for the cleaved-cavity-coupled (C^3) laser, the distributed feedback (DFB) laser /Kurumada 1984/, and the GRECC laser, which gains stability by an external resonator /Hecht 1984/. A C^3-laser holds the record for repeaterless transmission over 161.5 km at a data rate of 420 Mbit/s /Kasper et al. 1983/. With the same laser 1 Gbit/s transmission over 120 km has been performed /Linke 1984/.

- Use of a conventional multimode laser in conjunction with a dispersion-shifted fiber which is made broadband at 1.55 µm by a special design of the core profile. The key to controlling dispersion is to tailor the lightguide structure (core diameter, refractive index difference Δ) for a waveguide dispersion canceling the material dispersion at one or more wavelengths. As Fig.2.2 shows, it was possible, with a triangular graded-index profile shape fabricated in a MCVD process, to shift the dispersion minimum to 1.53 µm, where a loss of 0.21 dB/km close to the estimated intrinsic loss of 0.18 dB/km was measured /Cohen et al. 1983/.

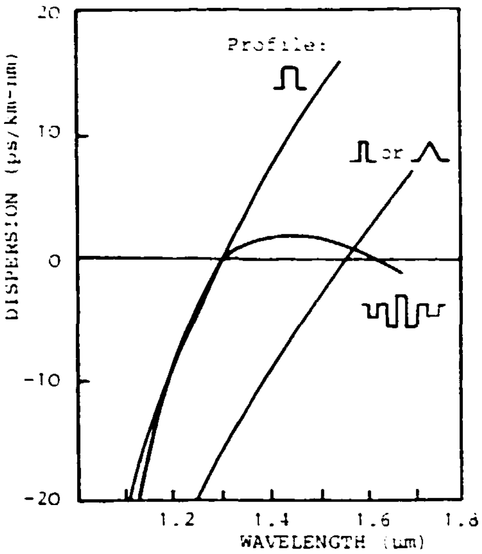


Fig.2.2: Examples of alternative chromatic dispersion spectra

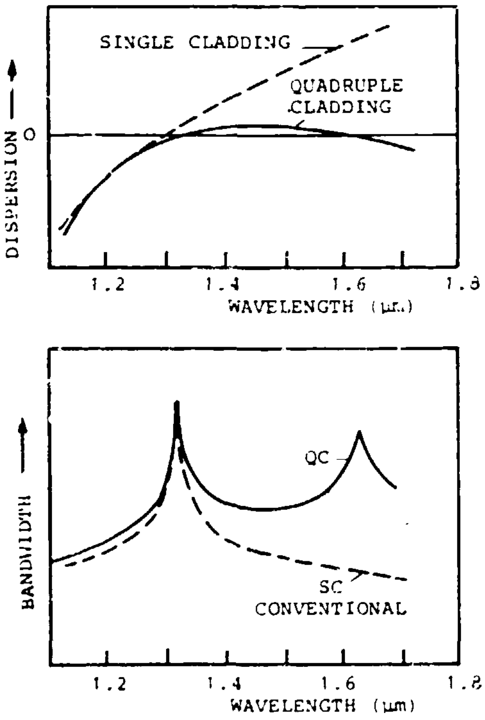


Fig.2.3: Transmission characteristics of a quadruple-clad fiber

Some research work is done in the investigation of materials other than silica glass suited for extremely low-loss transmission in the 2 - 5 µm region. For fluoride-based glasses (ZrF_4-BaF_4-GdF_3-AlF_3) theory predicts losses of 0.001 dB/km at 3.5 µm /Pearsall 1982/, which would make possible repeaterless transoceanic cables. The question is whether manufacturing processes can be established which are economic and can reduce the actual losses of some dB/km to the theoretical limit. Beyond that detectors and sources have to be developed.

There is a strong trend to use SM-fibers in long-haul systems. Whereas SM-fiber production has now rather matured, there remains work to be done in the field of splicing technology and connectors to yield routinely the encouraging results of laboratory work, where fusion splice losses of 0.03 to 0.1 dB and connector losses < 0.5 dB have been reported. Elastomeric splicing technology is developed as a possible alternative to the fusion splice. Coupling of the laser output power into the SM-fiber gives also room for improvement (now 5 to 6 dB loss).

A further trend points toward improved receivers. PIN-FET detectors are being rapidly developed to increase their sensitivity and to reduce their noise contribution.

Up to now simple on/off-keying in conjunction with direct detection is used in optical communications systems. Coherent detection schemes (heterodyne or homodyne detection) promise an improvement in sensitivity of 10 to 14 dB, already proven in experiments /Malyon 1984, Shikada et al. 1984/. The answer to the question whether the high technological effort with sophisticated transmitters/receivers will justify some more km repeater span is still pending. First field application of coherent systems will probably be in submarine links. More widespread use will depend on the development of low-loss polarization-preserving fibers or, even better, on the elimination of the need for such special fibers.

2.1.2 Medium-haul trunk lines

- Interoffice links: These systems connect two telephone central switching offices with a traffic ranging from tens of telephone channels (4 kHz ≙ 64 kbit/s each) to many thousands. A lot of such links are required in a telephone network. For low-capacity operation, the trend is to reduce components and fiber cost in order to compete with copper systems.

- CATV trunking: Common antenna TV or cable TV is the distribution of TV signals to subscriber homes by cable instead of by free-space radiation. The central distribution points called "hubs" receive TV signals from TV stations directly or via the headend (radio-link terminal). Trunking between headend and hub or between hub and hub by fibers has the advantage to obviate the need for a repeater, which is to be found every km in coaxial systems.

- Entrance links: Satellite ground stations and radio-link terminals are often located in relatively uncongested areas some km away from city centers. These are stations where large volumes of traffic converge. Optical fiber links can relieve the RF spectrum congestion which would arise if the connections to the city are via radio links. Analog transmission of the frequency-modulated 70 MHz intermediate frequency signal is possible but is limited to a few km due to the high signal-to-noise ratio required.

- Feeder transmission line: It connects the central office to remote switching units in the subscriber loop.

The lengths typical for the mentioned applications cover the range from 4 to 30 km, distances which are, at moderate data rates of typical 34 Mbit/s, bridgeable with multimode systems without the use of repeaters. Systems worldwide installed operating at 0.85 µm as well as 1.3 µm are proving economy and reliability. Due to the low dispersion and attenuation at 1.3 µm the trend is to use LEDs, which do not cause modal noise, are cheaper and easier to operate, and have practically unlimited lifetime ($> 10^9$ hours /Lee 1982/). Whereas up to now LEDs have been used only at moderate data rates, recently developed 1.3 µm edge-emitter types have been employed to demonstrate 560 Mbit/s transmission over a 4.4 km long GI-fiber /Grothe et al. 1983/. Successful 1.6 Gbit/s modulation of a 1.3 µm LED has also been achieved /Suzuki et al. 1984/.

Many existing metropolitan ducts are already now overcrowded. Wavelength-division multiplexing (WDM) will be the right tool to upgrade installed systems in order to cope with the increasing demand for more bandwidth. The alternative will be the installation of SM-fibers also for medium-haul trunks to provide the required unrepeatered transmission at 140 Mbit/s or 560 Mbit/s. It is widely anticipated that by-and-large the SM-fiber will penetrate into this market segment during the next years, if SM-fiber prices go down due to mass production.

For ultra-broadband WDM-applications the double-clad and the quadruple-clad lightguide structures are under development to provide low loss and to extend the near-zero dispersion region over a spectral range from 1.3 to 1.6 µm (see Fig.2.3,p.33) /Cohen et al. 1983/. Apart from low dispersion broadband WDM application requires the elimination of the OH-peak at 1.39 µm. The VAD process can provide this to keep the attenuation below 0.5 dB/km between 1.2 and 1.75 µm /Chida et al. 1982/.

2.1.3 Short-haul applications

In this class we find intrabuilding or intraplatform links over some hundred meters for data transmission at low to moderate rates (< 10 Mbit/s). The main task of these links is the undisturbed transmission in severe environment, which will be managed best by optical fibers. Various applications for control and surveillance (CCTV) in industrial and military systems benefit mainly from electrical isolation and the freedom of electromagnetic interference of optical fibers:

- Power plants
- Nuclear plants and laboratories
- Process control in chemical or explosive environment
- CAD/CAM
- Medical inspection
- Highway and railroad control (traffic signs)
- Data exchange along high-voltage power grids in fibers attached to or incorporated in power lines
- On-board data transmission (communication, control, monitoring) in vehicles.

The usual modulation format is PCM, but also analog transmission is employed for CCTV-surveillance tasks. In these cases bandwidth is easily conserved by lower frame-rates or reduced line numbers. The key point for more widespread use of fiberoptics in such applications is economy. Cheap active and passive components, using plastic materials to as large an extent as possible,will set the trend in this area. Because of use of plastics and high NA step-index fibers visible and near-infrared wavelengths are and will continue to be preferred.

2.2 Distribution systems

The distribution of a multiservice to a large number of users or subscribers (multi-user - multiservice)is a scenario of the future communications network. (It is an extension of the distribution of a single service such as the public telephone service.) The services to be distributed, and the physical structures (networks), where they are now distributed, are

- telephone in the subscriber loop
- data in the local area network (LAN)
- video in the cable TV (CATV) network

From the technical point of view optical fibers, with their inherent broad bandwidth, can realize such distributing systems with increased flexibility and capability. The economics of using fibers for these applications, however, have to be carefully checked in each application.

2.2.1 Subscriber loop - ISDN

The subscriber loop is the portion of the public telephone network that connects the subscriber's terminal sets to the nearest switching center. As illustrated in Fig.2.4 this is a central office (CO) or a remote switching unit (RSU) connected to the central office via a feeder (decentralized star type topology). For the originally intended purpose of the subscriber loop the transmission of analog voice signals with a bandwidth of 4 kHz the twisted copper pair has proven to be adequate, reliable, and cost effective. However, in addition to the basic telephone service, there is an increasing demand for the delivery of a wide variety of new services directly to the home or office, mainly stimulated by rapid advantages in the fields of electronic information processing, storage and retrieval, video recording, satellite communications, and microcomputers. Table 2.2 lists typical services being now under consideration. The provision of most of these services requires the transmission of broader-band signals (e.g. 30 MHz for a wide-screen high-definition TV channel with 1125 lines), signals of digital format, or signals requiring a higher level of performance. These challenges cannot be met by the existing loop plant. This fact has led to major interest in the extension of optical fibers from the trunk

Table 2.2: Services for the subscriber loop /Midwinter 1980/.

TYPE OF SERVICE	ONE WAY SELECTIVE OR DISTRIBUTIVE	TWO WAY OR MULTIWAY INTERACTIVE
Video	CATV pay TV High-definition TV video library access advertisements information/library educational surveillance	conference community relations video phone interactive education
Digital data	information - Viewdata, Teletext electronic mail using ASCII, etc electronic mail using facsimile remote blackboard or display electrowriter home newspaper remote library access data to home memory business data transfer Telex	adjunct to audio or video conference remote metering or control adjunct to educational or entertainment video homebanking teleshopping
Audio	audio information HiFi library access broadcasting	telephony HiFi conference

network through the loop plant network to homes and business premises as just one component in the development of a future broadband "integrated services digital network" (ISDN). An equivalent network now in Japan under development is called "Information Network System" (INS). Only if some broadband services are foreseen to be distributed in the local loop together with the conventional telephone service, the full benefit of optical fibers in the subscriber loop will be realized. First installations are expected to be for business customers.

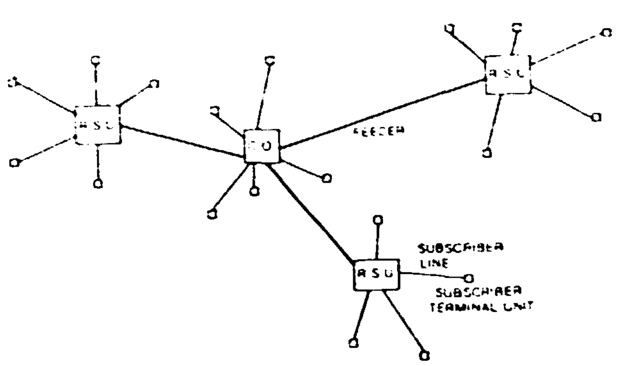


Fig.2.4: A star network topology with secondary nodes to reduce fiber requirements is used for the subscriber loop /Chang 1980), reproduced with permission.

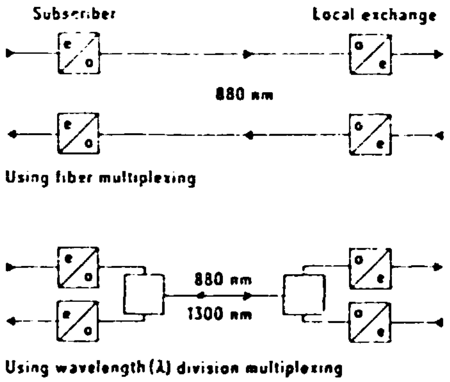


Fig.2.5: Bidirectional optical transmission on glass fibers
a) using fiber multiplexing
b) using WDM /Schenkel and Braun 1983/, reproduced with permission.

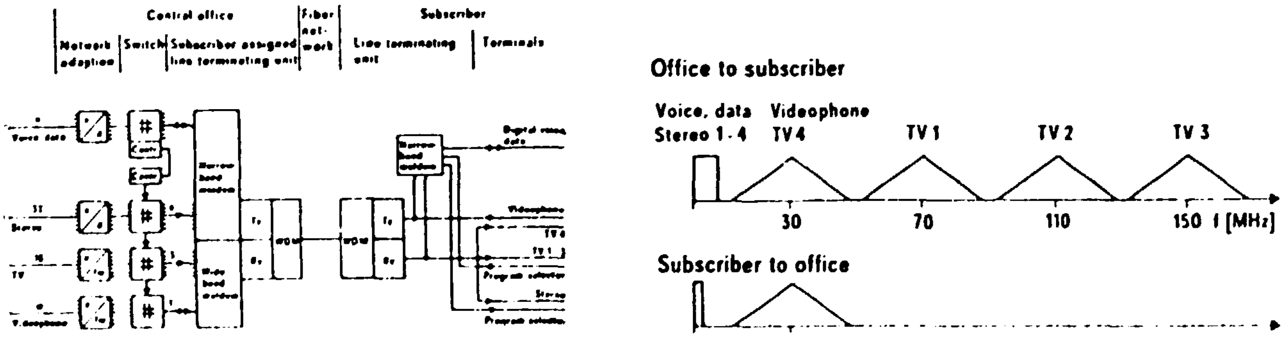


Fig.2.6: BIGFON switching concept and multiplexing plan as developed by Siemens /Schenkel and Braun 1983/, reproduced with permission.

There exists a strong trend toward such fiberoptic broadband switched networks although they are not yet well defined up to now. National plans for the implementation of such networks, and also existing field trials spread all over the world, differ widely, especially in the method applied to transmit a multiplicity of video channels along with voice and data signals over a single fiber. In /Heijden 1983/ the characteristic features of 26 trial networks are compared. Space-division multiplexing (SDM, two or four fibers in parallel), wavelength-division multiplexing (WDM), frequency-division multiplexing (FDM), and time-division multiplexing (TDM) are possible and commonly used methods. As Fig.2.5 shows WDM plays the important role for bidirectional traffic over one fiber. The challenging task for the TDM technique is the development of inexpensive VLSI digital video encoders, which is more important than a drop in the price of fibers. A typical concept for a broadband services subscriber loop as implemented in the BIGFON project of the German Federal Post Office /Schenkel and Braun 1983/ is presented in Fig.2.6.

Table 2.3 shows the maximum loop lengths achievable with GI-multimode fibers for several choices of optical components. For very long loops, which are often encountered in rural areas, single-mode fibers will be the

Table 2.3: Maximum fiberoptic loop length /Chang 1980/

Source & Detector	Operating Wavelength (μm)	Power into Fiber (dBm)	Detector Sensitivity (dBm)	Fiber Loss (dB/km)	Max. Loop Length (km)	
					bi-dir.	uni-dir.
LED	.8 - .9	-10	-27.9	4	2.5	3.0
PIN	1.1 - 1.6	-10	-27.9	2	4.9	5.8
Laser	.8 - .9	7	-29.2	4	6.9	7.4
APD	1.1 - 1.6	7	-29.2	2	13.2	11.2

Note: It is assumed that the connector loss is 2 dB (4 connectors with 0.5 dB loss each), the splice loss is 0.2 dB/km and, for the bi-directional loop, the insertion loss of the two couplers is 2 dB. In all cases, an optical margin of 3 dB is allocated. The fiber is assumed to be of graded-index type.

solution to avoid repeaters. Up to now it is not clear if SM-fibers will find general application in the subscriber loop. From the present point of view there are only two cases that require the high bandwidth of SM-fibers. The first is the introduction of high-definition TV with a capacity demand of 280 to 700 Mbit/s, the second is the implementation of a mere distributing network for TV without a switching feature. The technical feasibility of such a system providing more privacy has been demonstrated. 16 digital TV channels have been transmitted over 21 km SM-fiber at 1.12 Gbit/s /Baack et al. 1983/.

An interesting discussion about future application of SM-fibers is presently underway. It could turn out that technical requirements alone are not prerequisite for widespread SM-fiber use. As cost may go down to the level of high-quality GI-fibers soon, there is strong pressure of parts of the fiberoptic industry to promote SM-fibers. Advantages of such a trend would rest in unification of methods and components, and in laying the ground for possible future expansion of services. This is partly true also for LANs.

2.2.2 Local area networks

The family of computer networks, industrial control networks, airplane and ship buses, and other short (< 10 km, distance - multi-user links is called local area networks (LAN). Whereas most of these are still electrical networks (e.g. the IEEE 802 "Ethernet" bus type network), fiber-optic-based LANs are also starting to appear. The reason for the rising interest in optical networks can be found in the advantages of fibers in comparison to electrical cables: noise immunity, freedom from gound loops, high bandwidth and low weight. The higher bandwidth of optical fibers allows serial data transmission in comparison to parallel transmission in electrical networks. The information flow design criteria in optical networks do not differ from those in electrical networks. The classical network topologies like T-bus (also called linear network), loop, star and hybrids of all of them are also possible with fibers, but their implementation is different from electrical networks. This is a consequence from the lack of direct fiber access. Instead, more sophisticated couplers must be used for tapping.

As examples for the current trend we here present two popular network topologies for fiber optical implementations: the T-bus (Fig.2.7) and the star (Fig.2.8). Both networks are capabie of exchanging information between each of the terminals.

Basically fiber optical T-bus networks can only be used for a small number of users (typical 10 terminals) because of the subsequent coupler losses, when the signal travels along the fiber. The different dynamic range requirements of the receivers are also a problem.

The star network requires a higher amount of wiring, but offers a number of advantages. All receiver signal levels would be identical if the fibers would have the same length. Most important, it can accomodate more terminals because of its lower losses. In a star network the power decibels only decay as the logarithm of the number of terminals, whereas in a T-bus network the dependence is linear. The number of terminals can be increased by using lasers to launch a high power into the fiber network. Recently, a 200-Mbit/s LAN was demonstrated, where a constricted double-heterostructure, large-optical cavity laser delivering over 10 mW of optical power was used to drive 100 terminals in a hybrid star network /Hecht 1984/.

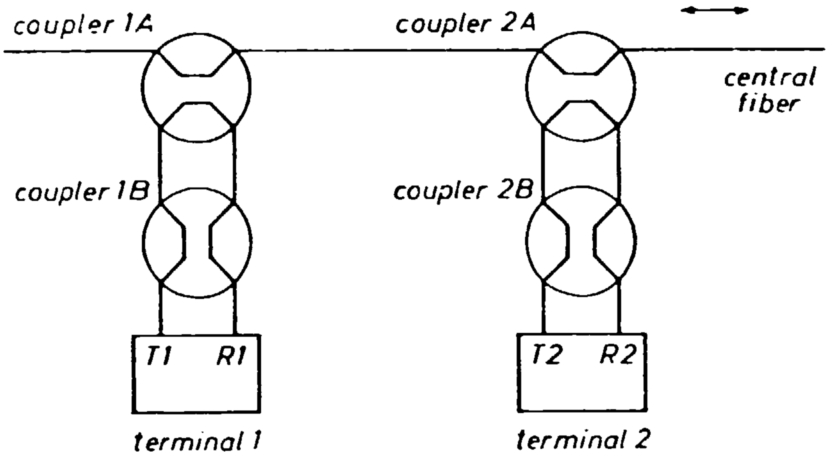


Fig.2.7: Bidirectional T-bus-type network.

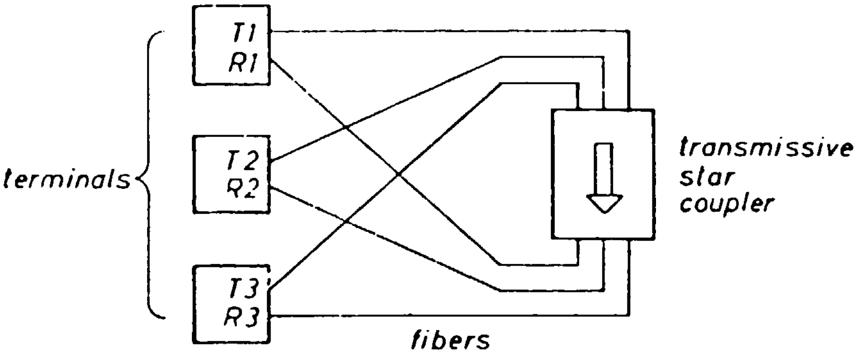


Fig.2.8: Star-type network topology.

Fiber networks are generally made with large core, large numerical aperture step-index fibers either low-performance silica, multicomponent glass, PCS, or all-plastic fibers and LEDs for reasons of simplicity. The lower bandwidth of these fibers is well suited to the required data rates, which usually is a few Megahertz maximum, if only data and voice and not video signals are to be transmitted.

2.2.3 Cable TV distribution

CATV systems as introduced up to now in various nations all over the world transmit simultaneously 12-30 TV channels via a tree-type branching network. Coaxial cables operated at the required bandwidth of 300 MHz distort severely the analog signals so that repeaters have to be installed every 300 meters. Although the optical fiber itself is a broadband transmission medium if only attenuation and bandwidth are considered, the nonlinearities of the terminal devices, particularly the sources, make it very difficult to use analog transmission for many simultaneous video channels on carriers. Penetration of this market segment by fiber-optics is expected to remain small. The alternative would be wideband switched networks as described in the ISDN concept.

2.3 Summary

The challenges of today's general telecommunication trends are met by fiberoptics through pursuit of vigorous R & D with the aims and relevant activities summarized in Table 2.4.

Table 2.4: 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	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

3. 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 (or monomode) fibers
- multimode fibers

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

- step-index fibers or
- graded-index fibers.

The parameter α (see Chapter 1) constitutes the distinction criterion. The range $1 \leq \alpha \leq 3$ defines graded-index (GI) fibers, the range $\alpha \geq 10$ step-index (SI) fibers. In the intermediate range ($3 < \alpha < 10$) the fibers are sometimes classified as "quasi-step-index" or sometimes just "step-index" (Fig. 3.1).

The term "polarization-maintaining" also refers to a light-propagation quality and designates a special kind of single-mode (SM) fiber. The overwhelming majority of present uses of this fiber is, however, in sensors not in telecommunications. This could change in the future if coherent detection systems should find wide-spread use.

The material of core and cladding may be glass or plastic and divides fibers into the following major categories (Table 3.1).

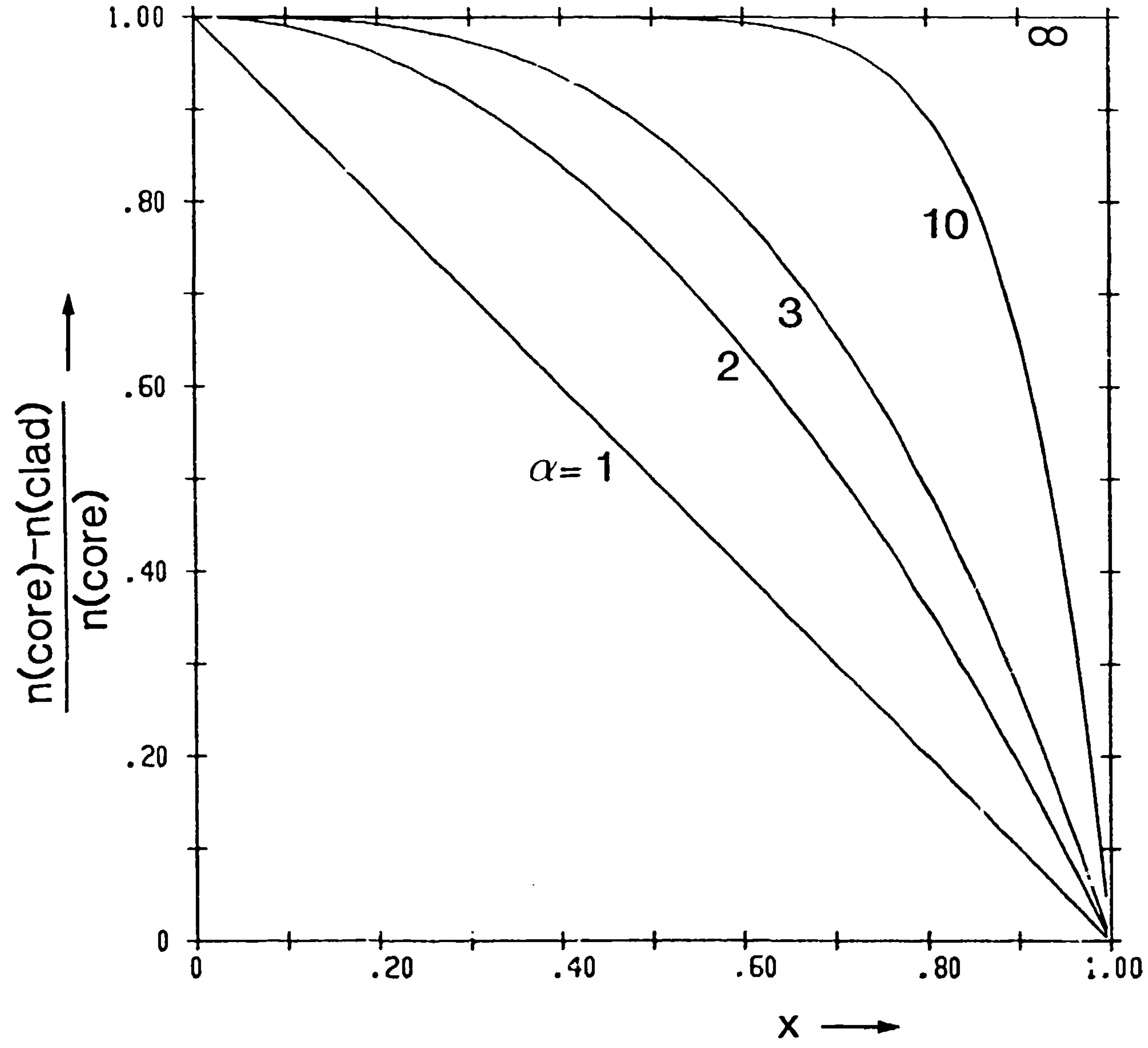


Fig. 3.1: Normalized index profile vs. normalized distance, x, from fiber center. Distinction between step-index (α>10) and graded-index (1≤α≤3) fibers is made according to α.

Table 3.1: Categories of multimode fibers by material of core and cladding.

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

[1] IEC Publication 793-1: Optical Fibres, Part 1: Generic Specification. Reproduced by permission of the International Electrotechnical Commission, which retains the copyright.

Single-mode fibers always have glass core and glass cladding.

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. Glass composition and doping exert decisive influence on fiber production.

Plastic materials suitable as cladding of glass fibers (plastic coated silica, PSC fibers) include /Tanaka et al 1975, Grabmaier et al 1977/ low-loss silicone resins and fluoridized polyalkenes and polymethylacrylates.

Plastic materials for all-plastic fibers share the requirement of (relatively) low optical loss with the mentioned cladding materials. However the choice is wider because their index of refraction does not have to be close to that of silica. It should be kept in mind that optical loss, even for suitable materials, is very high (100 ÷ 1000 dB/km).

The dimensions of core and cladding are closely related to the type of light propagation and to the fiber materials. For instance, core diameters about seven time as large as the light wavelength are required for single-mode fibers. Larger cores are inevitably associated with multimode fibers. Plastic coated silica fibers, to name another example, usually have large, uniform cores (≥ 200 µm) and exhibit a refractive-index step at the core/cladding boundary.

The technical issues behind the problems of standardization can be summarized as /CCITT Yellow Book/: The core diameter should be as large as possible to maximize source coupling, especially for LEDs, and to minimize splice loss. Large cores, however, are associated with higher material cost and higher microbending loss for a given cladding diameter. Other parameters affected by core/cladding dimensions include mechanical strength, manufacturing difficulties and, thus, cost . The tolerances on core diameter, concentricity and non-circularity mainly effect jointing loss and have to be traded off against manufacturing difficulties.

Table 3.2 compares existing international standards and additional, or deviating, national standards.

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.

The second standard in effect to date concerns category A3 fibers (plastic clad silica) /IEC Publ. 693/. Only the core diameter is specified:

International standard (A3 fibers)

Nominal core diameter: 200 µm

Table 3.2: Dimensional standards for graded-index fibers, category A1.

	International standards		Deviating national standards		
	IEC 693[1]	CCITT G.651[2]	ANSI/EIA RS-458/USA	Japan[4]	USA
Nominal core diameter	50 µm	50 µm	50 µm		
Core diameter deviation	NS	≤±6% (≤±3µm)	≤ ± 5 µm		
Non-circularity of core	NS	< 6 %	NS		
Nominal cladding diameter	125 µm	125 µm[3]	125 µm		
Cladding diameter deviation	NS	≤2.4% (≤±3µm)	≤ ± 6 µm		
Non-circularity of cladding	NS	< 2 %	NS		
Concentricity error	NS	< 6 %	NS		
Nominal core diameter			100 µm		
Core diameter deviation			≤ ± 5 µm		
Nominal cladding diameter			140 µm		
Cladding diameter deviation			≤ ± 6 µm		
Diameter first protective coating				400 µm	250/500 µm
Diameter second protective coating				900 µm	

It is assumed that core and cladding are substantially circular in cross section.

Literature: IEC Publication 693, Geneva, 1980; CCITT Yellow Book, 1981; CCITT COM XV-R39-E (Amended version of G.651), 1983; ANSI/EIA RS-458, 1981.

[1] Applicable to telecommunication and similar equipment, explicitly excluding "public telecommunication networks".

[2] Not actually a "Standard", but a "Recommendation".

[3] Note: If one or more coatings, which do not have to be removed for fiber jointing, enclose the cladding, the 125 µm value pertains to the diameter of this (these) coating(s).

[4] Agreed to by Japanese manufacturers.

[5] France has recently adopted a standard on fibers and cables (NF C93-850, 1983, HOM) in agreement with IEC 693 and further IEC documents, which are not yet internationally accepted as standards.

NS ... Not Specified

This standard is also intended to be non-exclusive. Common cladding diameters going with the 200 µm core are 400 µm, 380 µm, 330 µm and 300 µm. Other core cladding dimensional combinations of commercially available PCS fibers are: 150/250 µm, 200/330 µm, 250/380 µm, 250/580 µm, 300/440 µm, 400/450 µm, 400/500 µm, 400/550 µm, 400/560 µm, 400/600 µm, 600/700 µm, 600/750 µm, 600/850 µm, 1000/1100 µm, 1000/1250 µm. Larger core diameter is generally associated with lower optical loss and higher cost.

For <u>category A2 fibers</u> (all glass, step-index) no standards have been established yet. Many manufacturers offer fibers with dimensions 50/125 µm and 100/140 µm, but more than 20 different combinations are commercially available. They range from 45/50 µm to 800/1000 µm. They include special high NA fibers, very cheap (high-loss) fibers, and the glass composition varies widely. Evidently, there are many different uses for A2 fibers, a fact which makes standardization even more difficult.

<u>Plastic fibers (category A4)</u>, which are also not yet standardized, are manufactured with core diameter ranging from 100 µm to 6000 µm (6 mm!). The cladding dimension exceeds the core dimension by only 10% or less. Available plastic fibers share two characteristics: high numerical aperture ($NA \geq 0.5$) and high optical loss (100 to 1000dB/km). This reveals their standard use in short-haul transmission systems, with LEDs as transmitter.

For <u>single-mode fibers</u> there exist no international standards, but a cladding diameter of 125 µm ± 3 µm has been proposed in a CCITT draft recommendation /CCITT Study Group XV-Report R39/. 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 depend greatly on the wavelength used to convey the information. Three wavelength regions are in use today, a forth one ($\lambda = 1550$ nm) will be opened as R&D on fibers and components progress. Table 3.3 gives an overview on these regions.

Table 3.3: 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.

Besides the wavelength region, the paramount transmission criteria are:

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

Numerical aperture may also be used as a distinction criterion, particulary in matching a fiber to a given optical source. Dispersion is an alternate criterion to bandwidth.

A coarse classification of fibers according to their attenuation coincides with material, wavelength, and propagation classifications (Fig.3.2). Within each category, fibers with less attenuation are the more expensive ones.

For fibers intended for operation at two wavelengths (e.g. around 850 nm and 1300 nm) it is quite common to specify attenuation at each wavelength differently.

As described in the previous chapter, bandwidth is not easily specified in an unambigous manner. As a quick reference, coarse bandwidth categories are shown in Fig.3.3. There, the bandwidth of a length of fiber of 1 km is taken that is due to intermodal dispersion only. During manufacture, bandwidth is not yet a well-controlled parameter and the spread in this parameter is high. Manufacturer have therefore resorted to offering fibers in categories, for instance for graded-index fibers, of 200 MHz, 400 MHz, 600 MHz, 800 MHz, 1000 MHz and 1500 MHz. CCITT has adapted a similar philosophy but slightly different limits of categories: 200, 500, 800, 1000 MHz at 850 nm and 200, 500, 800, 1000, 1200 MHz at 1300 nm /CCITT COM XV-R39-E/. Each value is refered to a 1 km long fiber.

Numerical aperture values are tightly linked to certain fiber types, already categorized by other parameters. Table 3.4 gives a range of typical NA figures, less usual figures given in parenthesis.

Table 3.4: Typical NA of various fibers.

IEC category	Fiber	NA	Note
	single-mode	0.1 (0.12)	
A1	graded-index 50/125 µm	0.2 (0.16 - 0.22)	
	graded-index 100/140 µm	0.3	"high NA fiber"
A2,A3	step-index	0.2 - 0.5	
A4	plastic	0.5 - 0.66	

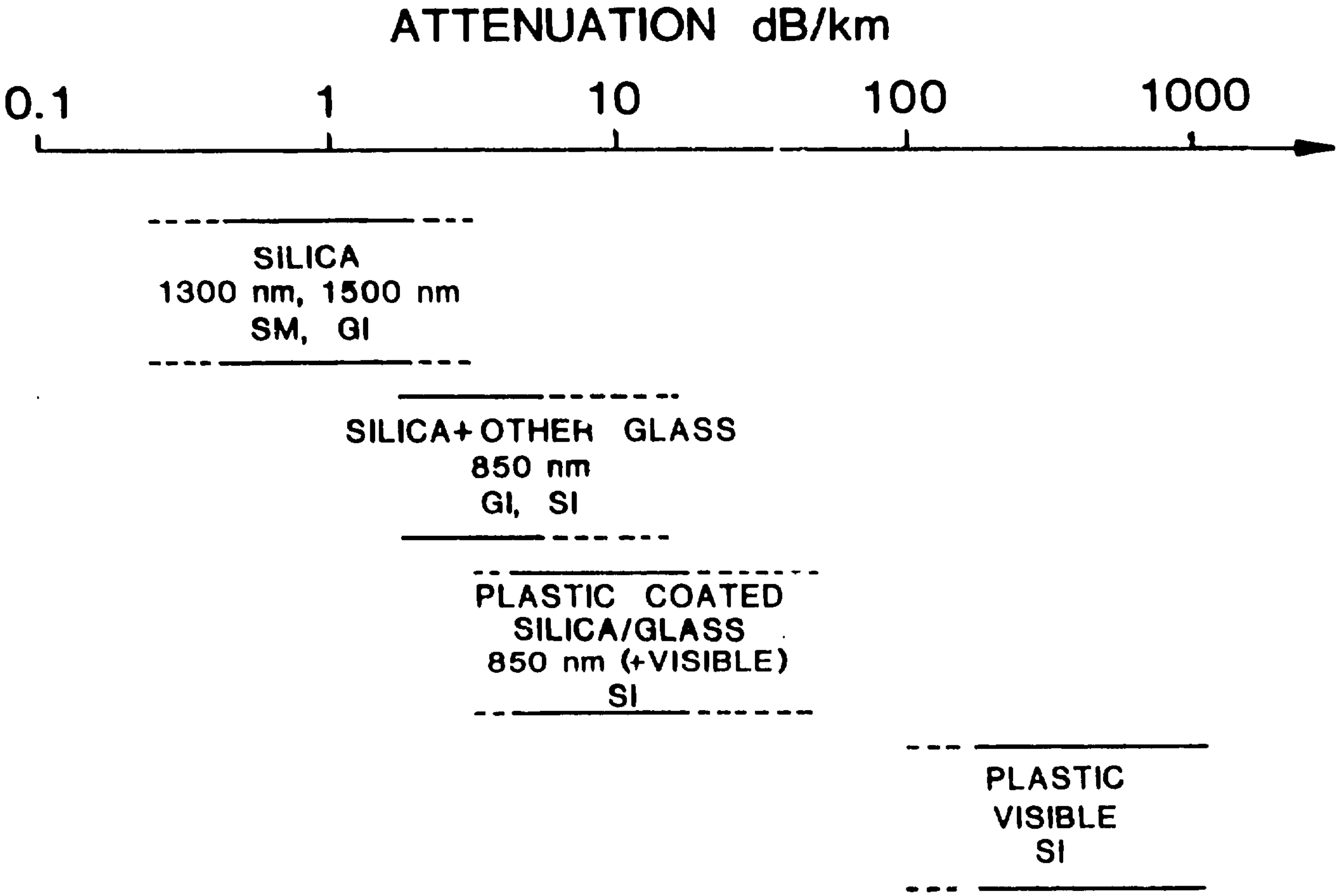


Fig. 3.2: Attenuation of optical fibers

SM single-mode fiber
GI graded-index fiber,
SI step-index fiber

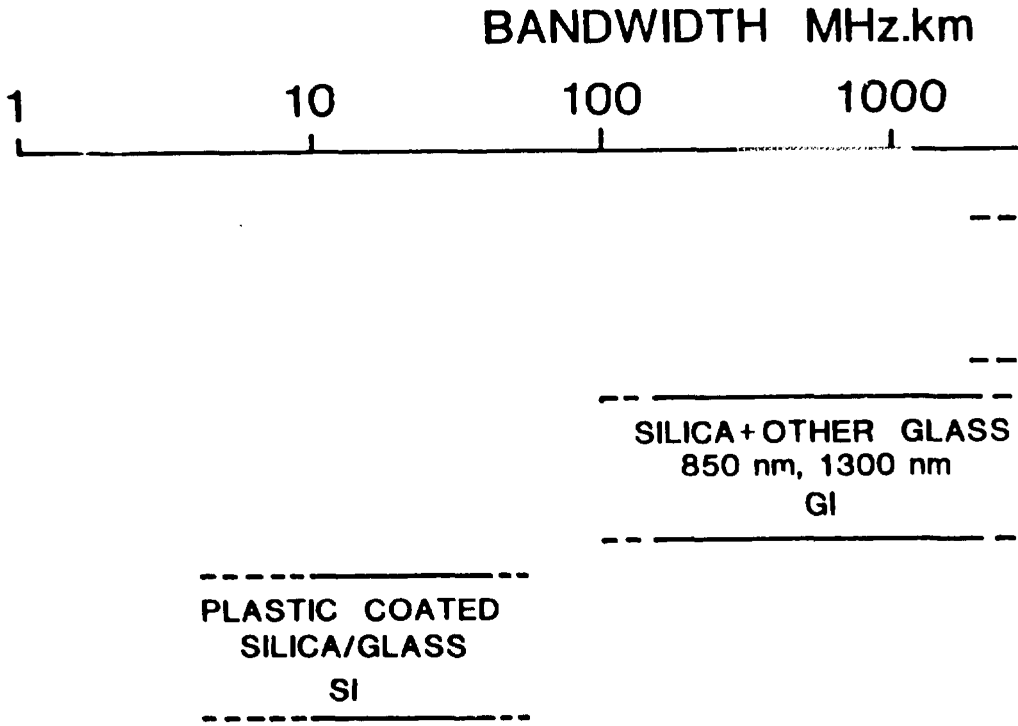
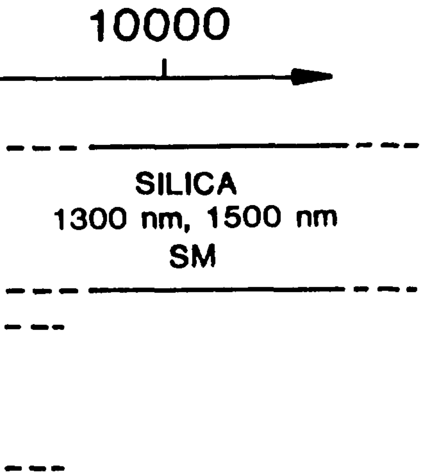


Fig. 3.3: Bandwidth of optical fibers

SM single-mode fiber,
GI graded-index fiber
SI step-index fiber


10000
SILICA
1300 nm, 1500 nm
SM

4. PRODUCTION OF OPTICAL FIBERS

4.1 General requirements

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!

Main criteria by which the quality of the produced fiber will be judged are:

- attenuation
- bandwidth
- mechanical strength.

A suitable production process must ensure compliance with some minimum requirements concerning these parameters. It must be suited in principle for fulfillment of these requirements, and it must also be suited for repeated production of fibers of a consistently high standard. Another question to be answered is whether fiber parameters are uniform over fiber length. In assessing the merits of a certain process it will be important to see if and where exacting production conditions can be relaxed without compromising quality (ease of fabrication).

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. Therefore, some basic questions should be asked about any production process. Are there critical process steps drastically reducing yield? Is tight control of process parameters essential for high yield? Is a continuous production of fibers possible? Can large length of high-quality fiber be produced? Is the length of fiber that can be produced in one stretch limited? Are any limitations in yield or production speed technological by nature, i.e. can they reasonable be expected to be overcome by intensified research efforts? Or are the limitations caused by an inherent process handicap?

A further important criterion of a production process should be versatility. Is the machinery suited for the production of a variety of optical fibers or just for one kind of, possibly limited or declining, application?

After an overview over the various production processes in the following section, each process will be described in detail and assessed by answers to the above questions in Sections 4.3 through 4.7.

Finally it should be noted that, before any actual fiber production can start, a carefully balanced first design of the desired fiber must come first. Such a design will determine diameter, Δ, index profile, cut-off wavelength, ... to fulfill given specifications of bandwidth, attenuation, numerical aperture and microbending sensitivity (compare Section 1.2). This design procedure is closely related to the choice of basic material and dopants. Fiber design will not be treated in this report. It must be kept in mind that refining the design of a fiber to achieve high performance is still by trial and error.

4.2 Overview over production processes

Basically, two paths can be followed to produce optical fibers (Fig.4.1):

- 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.

Making preforms for high-quality silica fibers (SiO_2), a general method called vapor-phase reaction, is used. (The sol-gel process of preform making is not used in actual production today, but is included in this study for its possible potential of cheap mass preform production.) 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, silicon tetrachloride ($SiCl_4$), is liquid at room temperature. As the vapor pressure of transition metal impurities which increase the optical loss, are much lower than that of $SiCl_4$, it can be distilled by using it in its vapor phase. The central portion of the preform designated to form the future fiber core or the adjacent layers of the cladding, are doped to increase or decrease the refractive index. Figure 4.2 shows the variation of the refractive index of silica with various amounts of common dopants. The effect of different profiles on light guidance has been discussed in Chapter 1.

Pure silica requires high temperature to become liquid. The addition of dopants, in particular germanate, borate and phosphates, reduces the melting point of the glass and increases its viscosity. Hard-glass fiber can therefore be said to be based on germanosilicate, borosilicate and phosphosilicate glass.

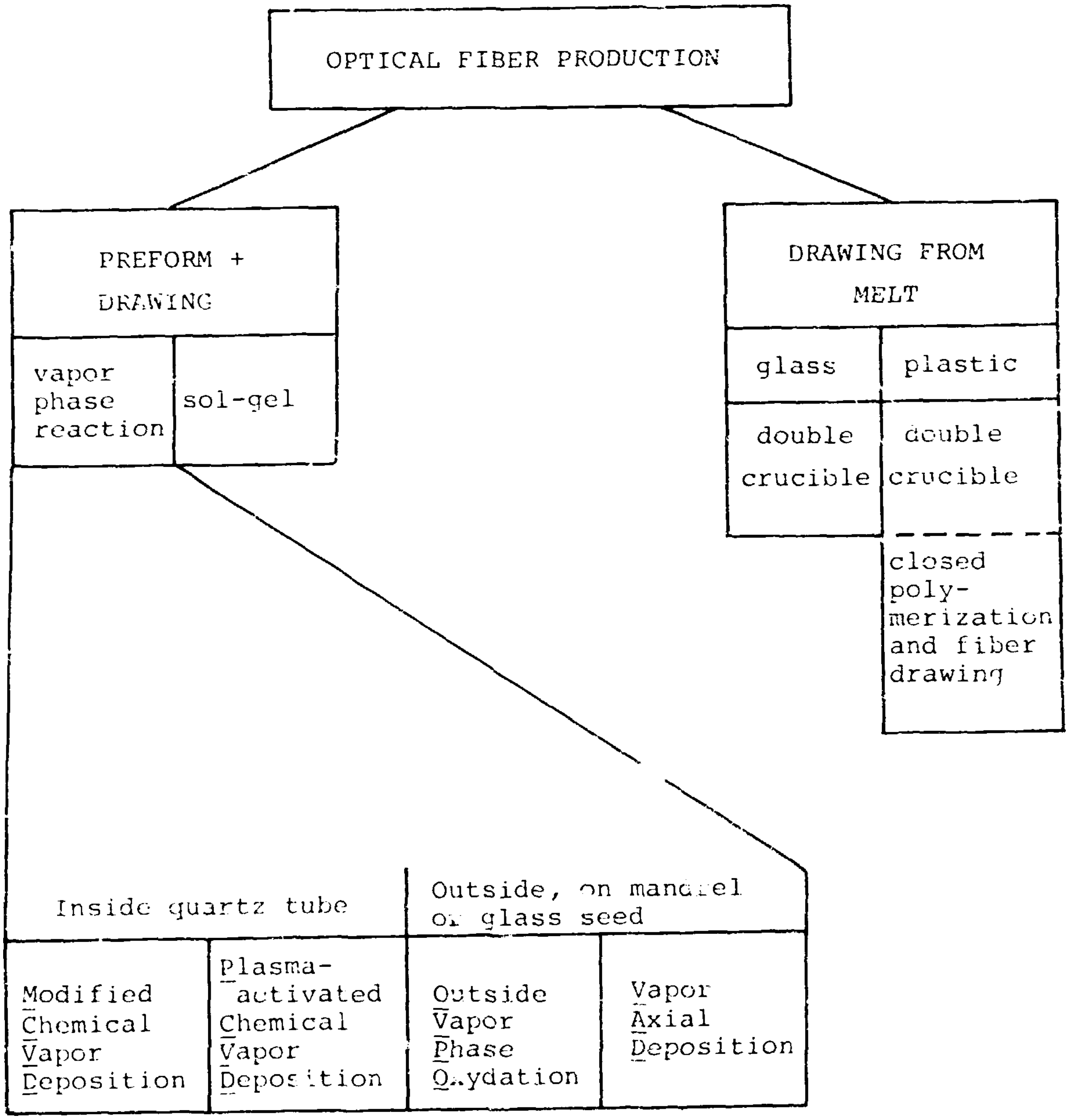


Fig. 4.1: Classification of fiber production processes

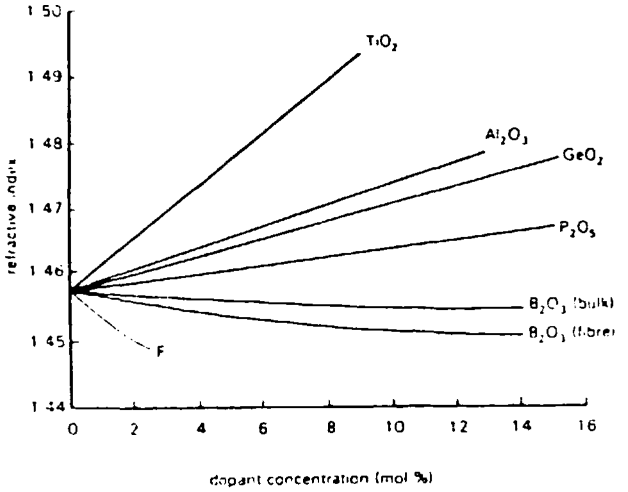


Fig. 4.2: Refractive index for various dopants in silica vs. dopant concentration /Nakahara 1981/, reproduced with permission.

Irrespective of the preform fabrication method, <u>fiber drawing</u> is achieved on drawing towers, at the top of which the preform is heated to silica melting temperatures (Section 4.4). When a refractive index profile has been incorporated into the preform, this profile is preserved in the drawing step. For protection against damage and contamination, one or more primary coatings are applied to the just-drawn fiber. Most common coating materials 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 methods relying an melting basic raw materials and <u>pulling</u> the optical fiber directly <u>from the melt</u> 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. A number of major optical fiber manufacturers have discontinued using this method. 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.

Before going into the detailed description of various production processes, three points should be noted. First, there is no such thing as a single "standard" process. Of each method, there are several variant procedures in use, sometimes within the same plant of the same company. The present status of a production process depends on the degree of mastering the subtleties of the process steps by the manufacturer, his willingness to invest in continuous development of the process, the date of purchase/ installation of existing parts of machinery, the patent situation, and, sometimes, on "company philosophy". Second, every process is continually being improved by the user. Thus, this report represents more or less a momentary picture of the situation. The section of production trends will give guidelines about the general direction of R & D in this field. Third, because of heavy commitment to R & D, many details of some production processes are proprietary or handled as trade secrets.

4.3 Preform fabrication

The four major preform fabrication processes are based on vapor-phase reaction or chemical vapor deposition (in the general meaning of the term). Two are chemical vapor deposition (CVD) processes in the narrow sense of the term, i.e. modified CVD (MCVD) and plasma-activated CVD (PCVD). The remaining two, OVPO and VAD, are sometimes refered to as "soot processes", as SiO_2 soot is originally formed by oxidation of Si in a hydroxy flame burner. Silica is the primary glass former, additions are made to alter its refractive index and to build a waveguide structure.

4.3.1 MCVD

This process was developed at Bell Laboratories /Mac Chesney et al 1974 a and b/ and subsequently applied and improved by many laboratories and factories all over the world.

The process 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, but other dimensions are in use. The OH content of the - predominantly used - Heralux WG tubes of Heraeus, Hanau, West Germany, is 150 ppm. (Tubes of other manufacturers may have lower OH content but also have inclusions or other defects leading to high loss and low fiber strength.)

The tube is then mounted in a glass working lathe, rotated and heated by one or several oxyhydrogen torches (Fig.4.3). A gas stream consisting of a carrier gas (O_2 or inert, like N_2 or Ar) which picks up 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

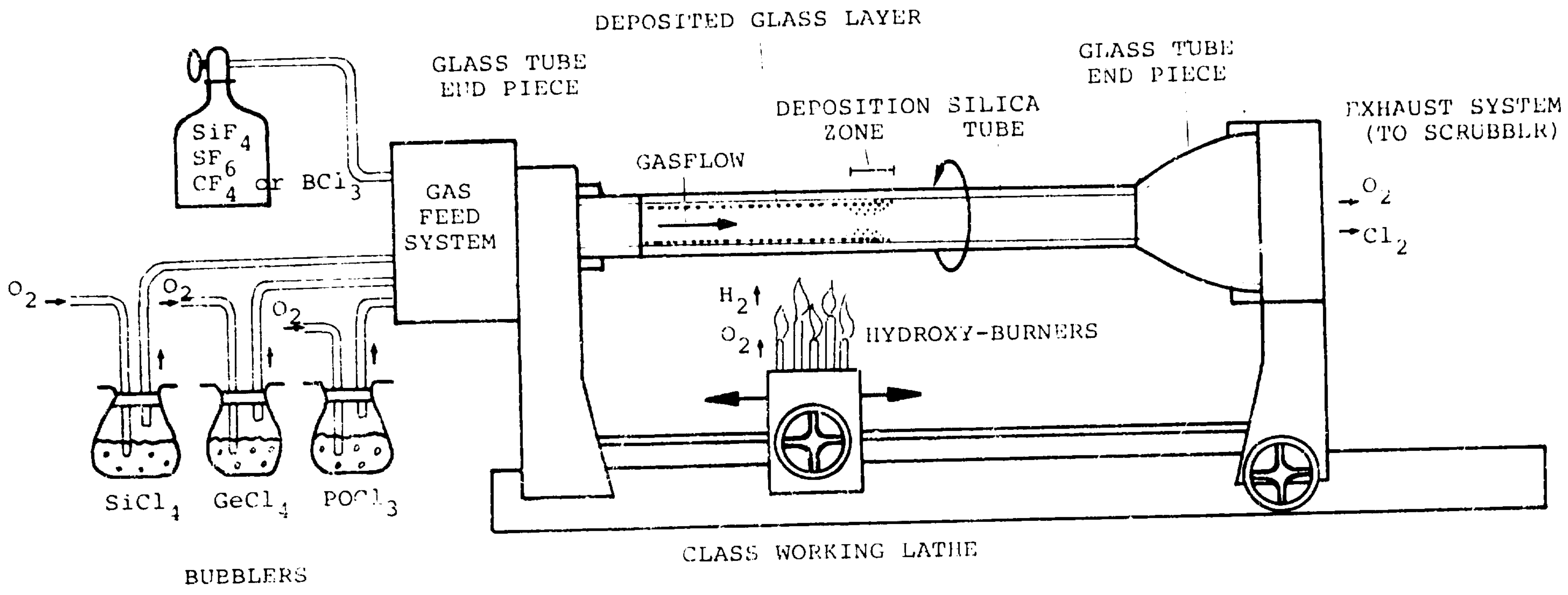


Fig. 4.3: Schematic of MCVD apparatus.

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. By appropriate deposition programs, both graded-index and step-index preforms can be fabricated. Finally, the tube including the deposit is collapsed into a solid rod, the preform, again by outside heating to silica softening temperature.

The gas feed system is a critical apparatus sub-system. It mixes, controls, and monitors the flow of the high-purity constituents of the gas stream. Halides, liquid at room temperatur like the most important silicon and germanium tetrachloride, $SiCl_4$ and $GeCl_4$, are contained in bubblers through which the carrier gas flows. Halides which are in vapor phase at room temperature, mainly fluorides, are added to the gas flow from pressurized gas cylinders. A gas-tight swivel system feeds the gas to the rotating tube.

Modern apparatus operates under microcomputer control to feed the required amounts of carrier gas and dopants, to move the torch and to regulate tube temperature. This is true for all CVD processes to be described. In modern plants each MCVD apparatus is operated in its own enclosure, partly transparent for visual control.

The effluent stream from the tube contains a mixture of both solids and gases including SiO_2, GeO_2, Cl_2 and unreacted $GeCl_4$. A wet scrubber in which water is added, the acid solution neutralized, and solid particles filtered out is ordinarily used. Recently, a recovery system for the expensive germanium was described /Bohrer et al 1983/.

/Nagel et al. 1982/list the various process steps in detail (Fig.4.4).

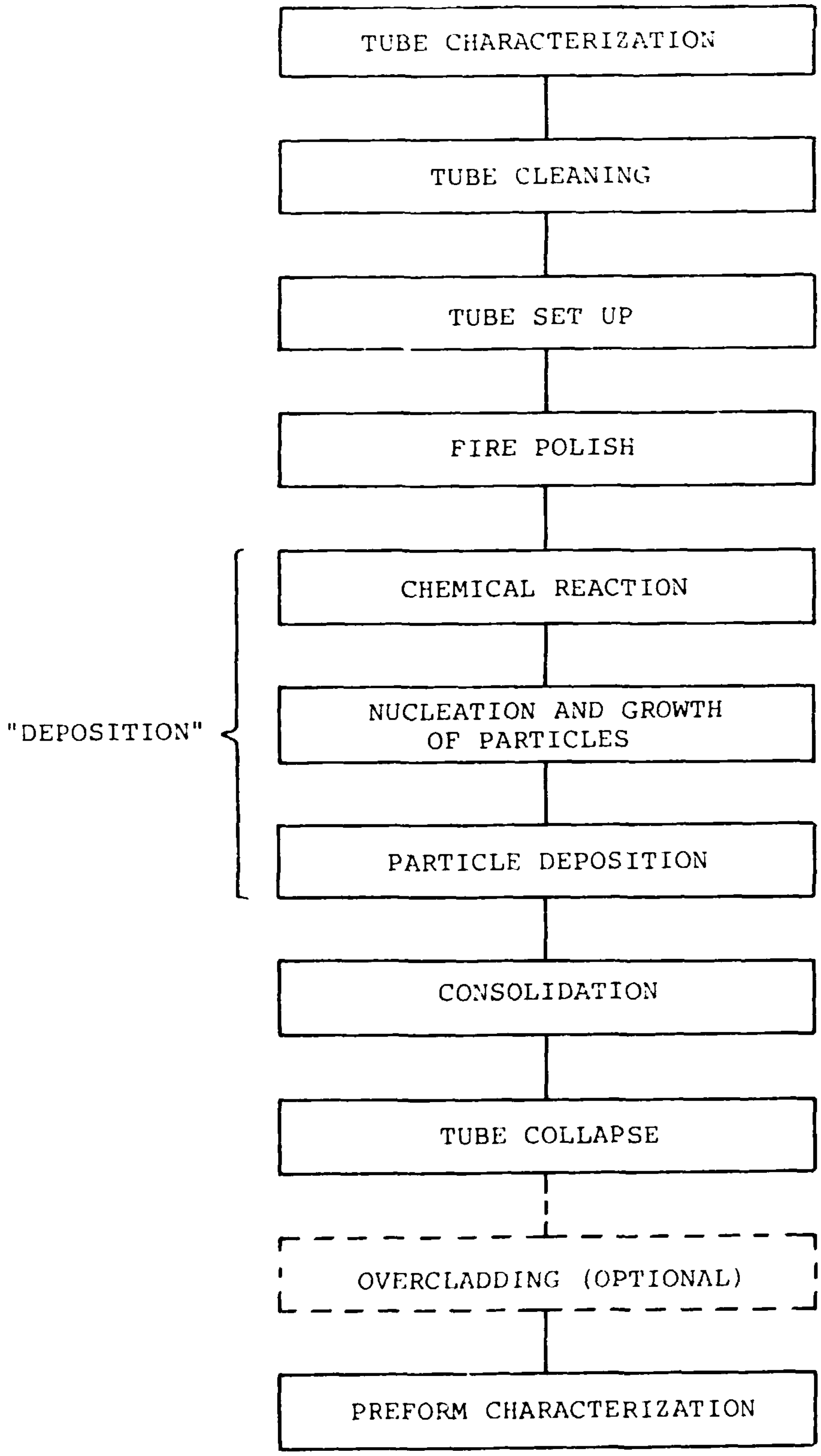


Fig. 4.4: Steps of MCVD preform fabrication process.

Tube characterization: The tube is measured for overall size, end-to-end variations, bow, ovality and siding.

Tube cleaning: The tube is usually subjected to a degreasing step and an acid etch to remove any debris or contaminants that could lead to bubbles or impurities.

Tube set up: The tube is fastened in the precisely aligned chucks of the lathe. Often the tubes have end pieces - e.g. rejected material from previous fabrication runs - which are melted onto it. A stress-free joint is mandatory. Great care has to be taken that the tube runs true which is important for the subsequent high-temperature steps. The connection to the gas feed system must be leak-tight. Proper tube set up is a delicate work requiring skill and experience.

Fire polish: This step consists of running the torch across the tube length and heating the tube to almost 2000°C. A pyrometer monitors tube temperature and serves as sensor for a flame control loop controling tube temperature to ± 2 °C. Fire polishing serves to remove any surface irregularities and to shrink any residual bubbles in the tube.

Deposition: The tube being set up, the deposition program can be started. First, the tube must be heated up. Then, a pure silica buffer layer of some 10 - 15 µm is deposited. This layer prevents OH to leak from the substrate tube to the center portion of the future fiber where it would cause dramatic loss increase.

From a chemo-physical point of view, the process step "deposition" actually includes several reactions and mechanisms /Nagel et al. 1982/. They are described in some detail because of their dominating influence of the future fiber. The oxidation reaction

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

commences between 1000° and 1300°C, above 1500°C all $SiCl_4$ is oxidized to SiO_2. $GeCl_4$ only reacts partially to form GeO_2 up to temperatures of about 1550°C. But at higher temperatures, the high Cl_2 pressure resulting from $SiCl_4$ oxidation increasingly prevents GeO_2 formation.

The problem is to find an outside-tube temperature consistent with an inside-tube temperature distribution which favors oxidation, deposition and sintering. MCVD is typically operated at outside temperatures >1500°C, the exact value depending on the amount of dopants and their composition.

The incorporation of OH ions into the preform is to be avoided in this process stage by: (i) excess Cl_2 present which binds hydrogen present to HCl; (ii) careful purification of starting chemicals; (iii) lowering O_2 partial pressure by using argon or helium as buffer gas or lower excess O_2 flow.

The deposition mechanism of particles in MCVD is called thermophoresis: A suspended particle in a temperature gradient experiences a net force in the direction of decreasing temperature. Figure 4.5 (page 72) shows typical particle trajectories in MCVD. The deposition efficiency ε is given by $\varepsilon \approx 0.8[1-(T_e/T_{rxn})]$, where T_e is the equilibrium temperature at which the gas and tube wall equilibrate downstream of the hot zone and T_{rxn} is the temperature at which the chemical reaction to form particles occurs. The value of T_e is an important process parameter which will depend strongly on torch traverse length, torch traverse velocity, ambient temperature and tube wall thickness.

Deposition cannot be arbitrarily raised by increasing flow rate, because there might exist regions in the tube center where T_{rxn} is not reached. To avoid this situation three counteractions have been proposed /Nagel et al. 1982/:

(i) use low flow rate; (ii) add He to the gas stream to increase thermal diffusivity together with broad hot zones; (iii) operate with high wall temperature. Control of T_e is necessary to minimize deposition tapers. In any case, an entry taper near the input of the tube cannot be avoided. Its length is of the order of 15 cm, and can be minimized by the addition of He to the gas stream and water cooling of the tube outside. The tapered section is scrap.

Consolidation: Since the deposited particles do not exhibit a glassy texture yet, a consolidation step via viscous sintering is necessary. In MCVD, this step follows deposition immediately by the torch sweeping along the tube. Bubbles in the preform can be a result of incomplete consolidation (or excessive deposition temperature), so optimization of operating conditions is mandatory. Under certain conditions /Walker et al. 1980/, addition of He and/or using a broader hot zone are beneficial to proper consolidation. Usual temperature is 1500 - 1800°C.

Collapse: The collapse phase takes up a considerable portion of the entire preform fabrication process and serves to make a solid rod of about 1 cm diameter out of the original hollow tube. In MCVD, the consolidated preform can be left in place and the collapse step may be performed (or not) on the same lathe. Several passes of the burner, say six, are standard for complete collapse. It is advantageous to perform collapse under defined pressure /French and Tusker 1979/ which the exit end of the tube sealed off, and heating while traversing in the opposite direction of deposition. As high temperature favors low viscosity, collapse is performed at high temperatures (1900 - 2100°C). An upper temperature limit is set by fluid flow of the heated rotating tube and tube deformation. A problem inherent to MCVD is also GeO volatization ($GeO_2 \rightarrow GeO(\uparrow) + 1/2\ O_2$) at the internal surface of the collapsing preform. A central dip in the index profil results which may or may not degrade the bandwidth of the future fiber. Countermeasures include controlled influx of $GeCl_4$ to compensate for GeO_2 burnoff /Akamatsu et al. 1977/. This becomes difficult when Cl_2 or $SOCl_2$ is employed as drying agent to reduce OH content. Optimum collapse conditions are to be found by experimentation.

Overcladding: In order to add cladding material of not-so-critical quality or to adjust core/cladding ratio, a silica tube can be slipped over the collapsed preform and melted onto it. This process also takes place on the rotating lathe and the usual torch is the heat source. The advantage offered lies in easier control of the deposition process for thin-walled tubes. Evacuation of the space between rod and overcladding tube aids in better dimensional control of the overcladding step. Temperature is in the 1900 - 2100°C range to melt the overcladding tube. Excessive material flow and stress build-up must be avoided.

Preform characterization: The preform's dimensions are taken and documented. The preform is checked for bubbles. Careful handling is mandatory (workers wear gloves). The preform is then stored in a clean place before drawing.

To enhance the deposition efficiency of MCVD, plasma-enhanced MCVD has been proposed /Jaeger et al. 1981/. The steps "particle deposition" and "consolidation" of Fig.4.4 are performed by separate heat sources. The other steps of the diagram 4.4 are not changed, with the possible exception of "chemical reaction" and "nucleation and growth of particles". Figure 4.6 shows a schematic of RF plasma-enhanced MCVD. The RF power of ~12 kW at 3 - 5 MHz is supplied to the coil which heats up the oxygen plasma to ~10^4°C. The plasma is operated at atmospheric pressure. Flowing water cools the surface of the substrate tube to prevent tube distortion. The existing large temperature gradient provides a large thermophoretic force for high deposition efficiency. Deposition rates up to 5g/min have been achieved in the laboratory

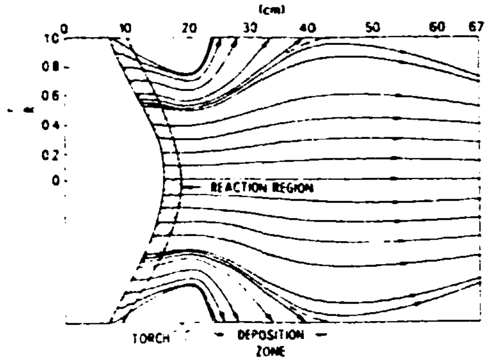


Fig. 4.5: Particle trajectories in MCVD /Nagel et al. 1982/, reproduced with permission.

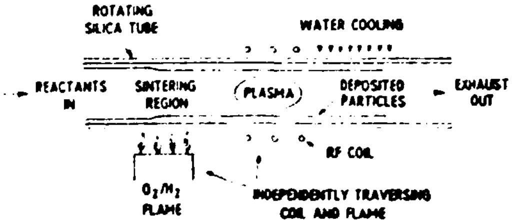


Fig. 4.6: Schematic of the RF plasma-enhanced MCVD process /Nagel et al. 1982/, reproduced with permission.

/Nagel et al. 1982/. Large inner diameter tubes (>40 mm) have to be used as substrates to avoid close contact of the plasma. Thick layers (~50 µm) can be deposited. All conventional MCVD dopants can be used.

4.3.2 PCVD

PCVD stands for plasma-activated chemical vapor deposition. This process was pioneered by Philips /Geittner et al. 1976/. The principal process steps are shown in Fig.4.7. The steps "tube characterization", "tube cleaning", "tube set-up", "fire-polish", and "collapse" are the same as described in the previous section. The main difference (and advantage) of PCVD as compared to MCVD is that a non-isothermal plasma initiates a heterogeneous 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 is almost 100% and about 85% of GeO_2.

Figure 4.8 shows a schematic of the process. A furnace heats the rotating substrate tube to 1200°C. A microwave resonator around the tube transfers electromagnetic energy of the order of 1 kW to the inside of the tube, where a low-pressure (range 1 kPa to 4 kPa) non-isothermal plasma is formed. A pump provides the necessary vacuum.

Deposition: Deposition of SiO_2 and GeO_2 occurs heterogeneously (i.e. only on the tube wall) upon initiation of the plasma. The 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. Only the core (and a buffer layer) are deposited for GI fibers. Ordinary deposition rate is 0.5 g/min, maximum rates of 1.3 g/min have been obtained /Koel 1983/. Deposition rates can be raised by increasing microwave power.

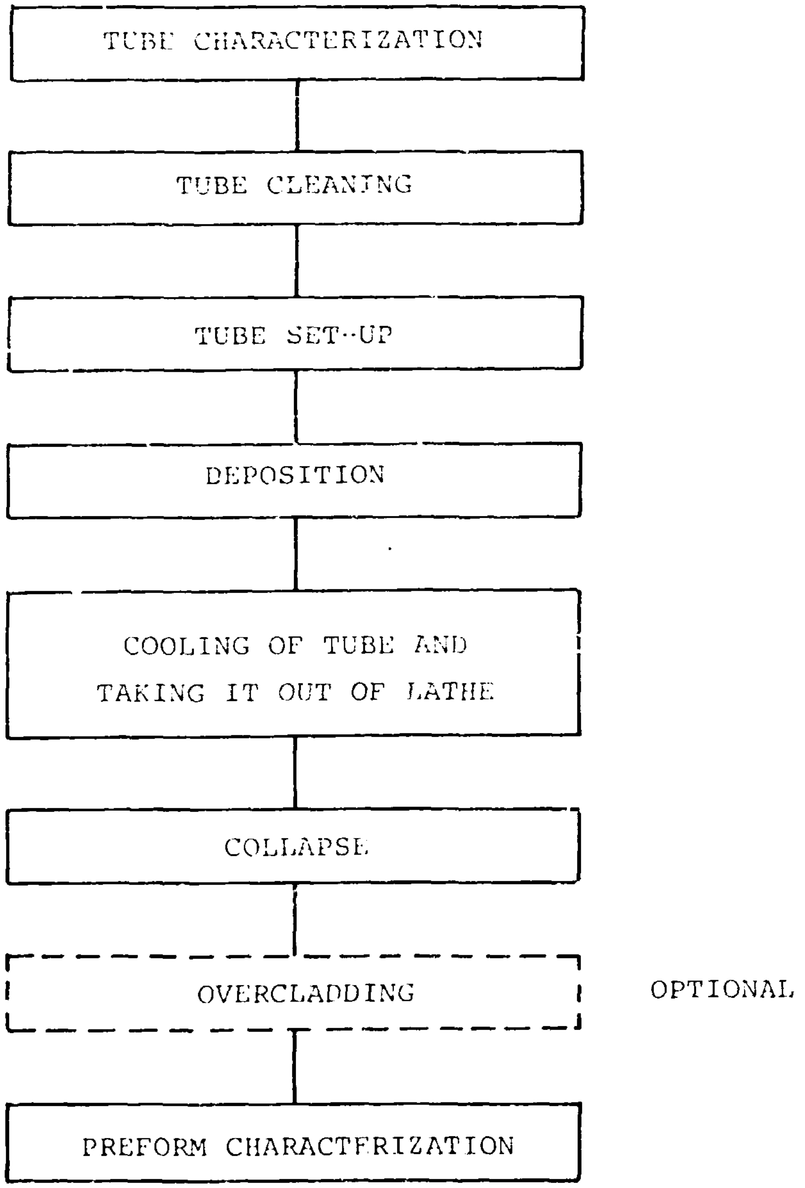


Fig. 4.7: Steps of PCVD preform fabrication process.

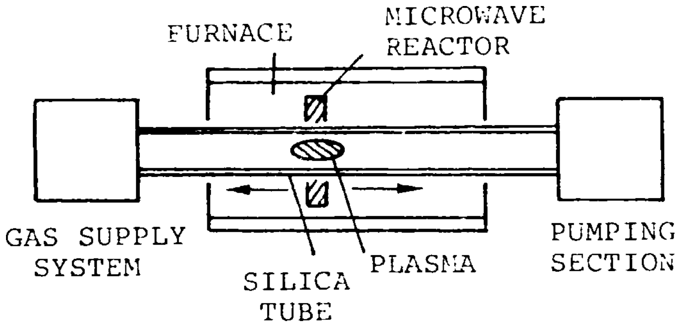


Fig. 4.8: Schematic of PCVD process.

4.3.3 OVPO (OVD)

Outside vapor-phase oxidation was invented by Corning Glass Works /Keck et al. 1973/. This company prefers to name the process outside vapor deposition (OVD). The following process steps are essential (Fig.4.9). Figure 4.10 shows the schematic of the deposition and of the sintering (= consolidation) step. 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. 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.

The OVPO process details are the least publicized. The ensuing description is based on /Schultz 1980, Blankenship and Deneka 1982, Morrow and Schultz 1984/ and a personal visit to Corning's research laboratory.

Mandrel set-up: An Al_2O_3 ceramic or graphite rod of about 5 mm diameter serves as a mandrel or target rod; length is up to 1 m, but usually less in production runs. This rod is held in a lathe.

Soot deposition: Silica soot particles are formed in the flame of a methane/oxygen or hydrogen/oxygen burner by thermally activated homogeneous oxidation. The burner has several concentric outlets. The center nozzle is for the glass forming vapors ($SiCl_4$, $GeCl_4$, etc. - compare Section 4.3.1). An adjacent nozzle is for an inert gas (e.g. Ar) preventing premature reaction of the chlorides with the oxygen coming through the outer nozzle along with the fuel gas (CH_4, H_2). Fuel gas consumption is in the range 5-10 l/min. The stream of hot glass soot emitted from the flame is directed to the mandrel, some 15 cm away. The glass soot sticks to the mandrel in a partially sintered state. The core and the cladding

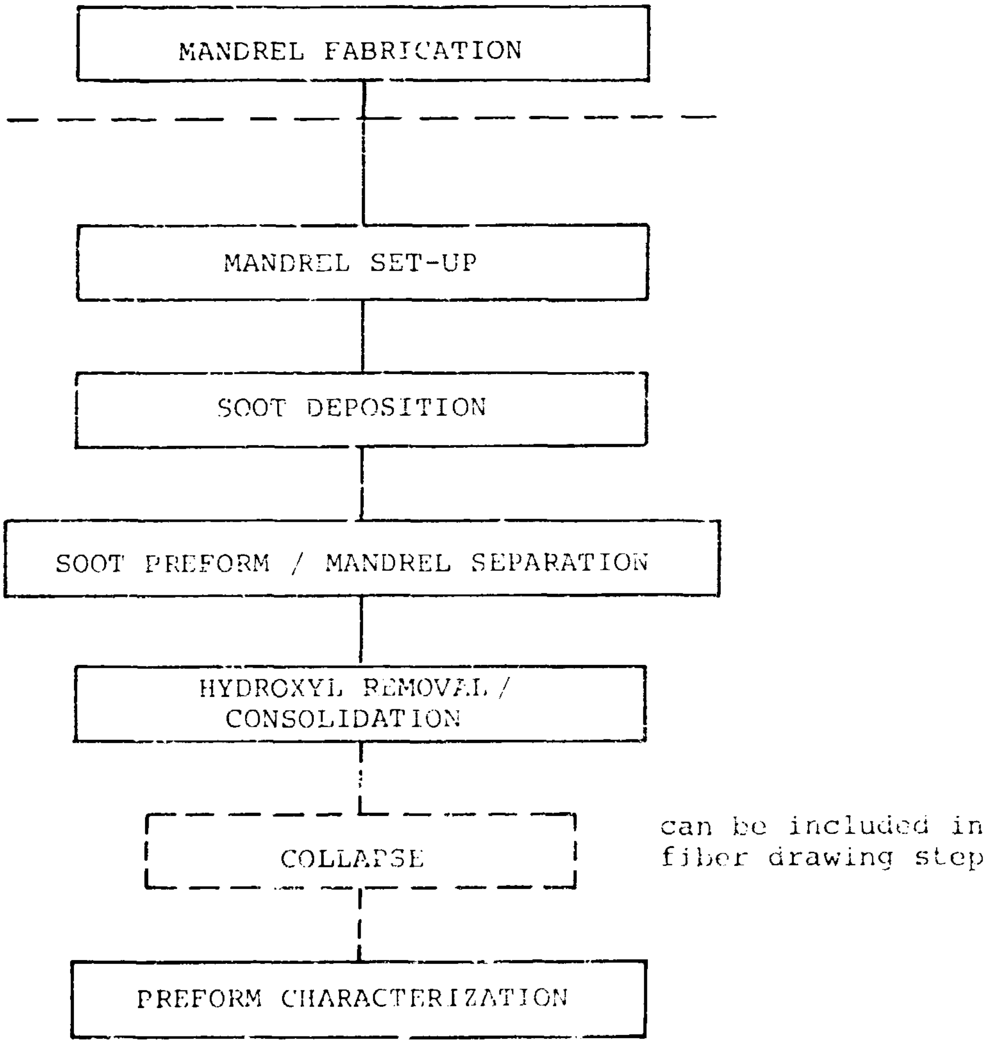
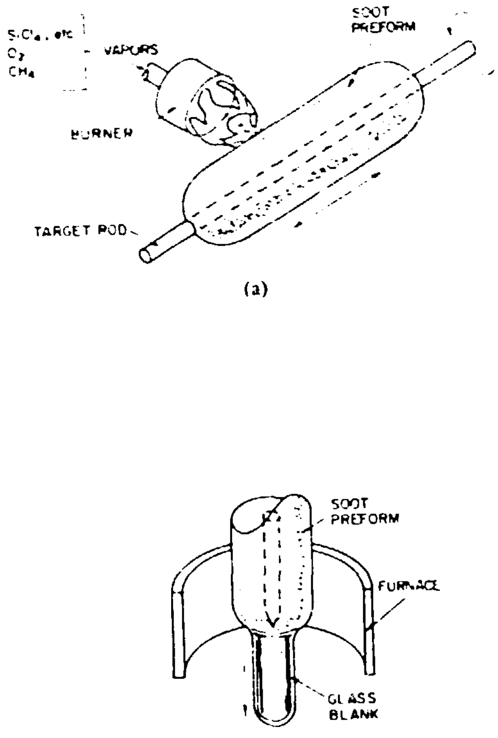


Fig. 4.9· Steps of OVPO preform fabrication process.



(a)

(b)

Fig. 4.10: Schematic of OVPO process
(a) Deposition, (b) Consolidation
/Schultz 1980/, reproduced with permission.

are built up layer by layer when the rotating rod is laterally passed by the burner. Deposition rate is up to 5 g/min (deposition efficiency ~50%). A large number of layers (typically several hundred) permit tight control of index profilevia vapor and deposition composition.

Soot preform/mandrel separation: The porous preform is slipped off the reusablemandrel by a proprietary method. This might be a critical production step.

Consolidation and hydroxyl removal: The porous preform is supported from one end and passed vertically through the hot zone inside a refractory muffle furnace. Viscous sintering is accomplished at hot-zone temperatures around 1500°C. The atmosphere consists of helium with a few percent of chlorine gas. Helium ensures bubble-free transparent preforms, Cl_2 purges the glass from OH content by the reaction

$$2(Si-OH)+Cl_2 \rightarrow SiO-Si+2HCl+\frac{1}{2}O_2 \ .$$

This treatment reduces the hydroxyl level from as high as 200 ppm to below 0.1 ppm. Details of the consolidation/hydroxyl removal procedure are described in Section 4.3.4 for the VAD process.

Collapse: The transparent preform obtained by the previous step may be collapsed in another furnace at 1800 - 2200°C, depending on glass composition, to eliminate the central hole. Alternatively, this step is omitted and the glass blank with the central hole heated right away in the drawing furnace, in which the fiber is drawn (compare Section 4.4). (Preform characterization: as described in Section 4.3.1.)

1.3.4 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.4.11). As in the OVPO process, glass particles of size 0.05 µm to 0.2 µm are synthesized in the flame of an oxy-hydrogen 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, which has an apparent density of 0.2 - 0.4 g/cm^3, 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) /Izawa et al. 1977/ and is used by the major Japanese fiber producers (Sumitomo, Furukawa, Fujikura), at least partially.

The process steps for making preforms by the VAD technique are shown in Fig.4.12.

Seed rod set-up: The seed rod, usually made from silica is clamped into the chuck of a vertically pulling machine. The seed rod diameter matches the diameter of the future consolidated preform.

Soot deposition: The oxy-hydrogen burners have several concentric nozzles into which are fed O_2, H_2 and $SiCl_4$, $GeCl_4$, and $POCl_4$. An inert gas, Ar, flows between the O_2 and H_2 outlets to prevent damage of the burners. Typical gas consumption per burner would be 7 l/min O_2, 4 l/min H_2, and 1 l/min Ar. For single-mode fiber production, two burners are usual: one for core, the other for cladding deposition. For graded-index fibers, one burner suffices, but several burners increase deposition speed. To make a desired refractive-index profile, it is necessary to carefully control the

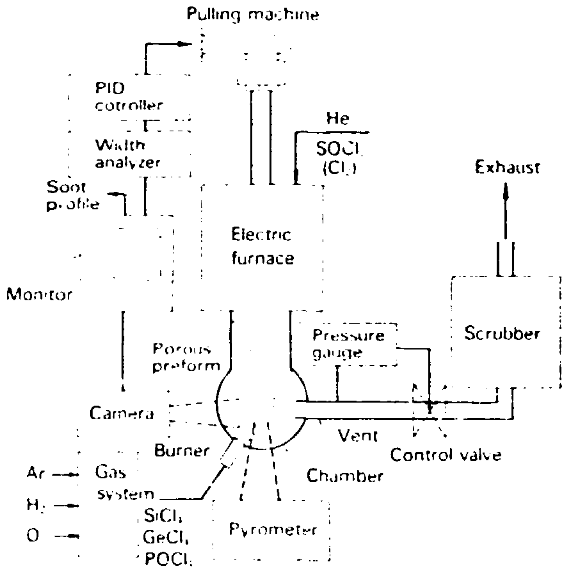


Fig. 4.11: Schematic of VAD apparatus /Inada 1982/, reproduced with permission.

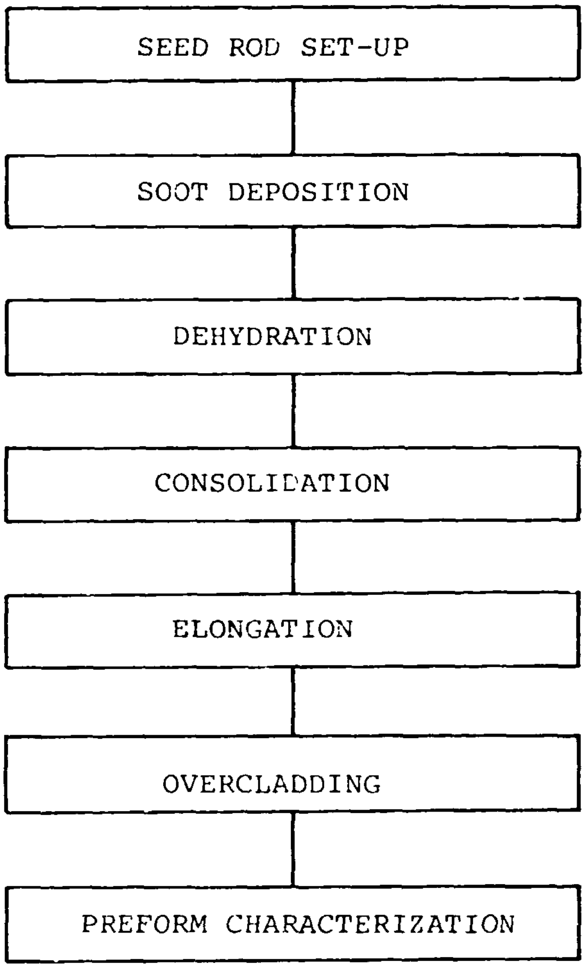


Fig. 4.12: Steps of VAD preform fabrication process.

following parameters: nozzle structure, burner position, flame temperature, nozzle-preform distance, raw material vapor flow, H_2/O_2 ratio, shape of preform, surface temperature of preform. The last parameter, which is monitored by a pyrometer, mainly determines the GeO_2 concentration and therefore the profile /Inada 1982/. By two-dimensional mapping of the preform surface temperature ($\sim 500 - 900^{\circ}C$) computer control of gas composition/flow rates and of pulling speed permits fully automated soot preform production. Closed-circuit TV and He-Ne-laser sensors aid in soot profile and preform end determination, respectively. To preclude preform ellipticity, the pulling apparatus has to run true. Since not all the produced soot is actually deposited on the preform, the surplus soot "fog" is mechanically removed from the reaction vessel. Small evacuating pipes keep vision ports free from soot precipitate.

<u>Dehydration:</u> Four sources of OH ion contamination have been identified by /Chida et al. 1982a/: raw material impurities like $SiHCl_3$, SiH_2Cl_2, and HCl, producing Si-OH; direct contamination from the oxy-hydrogen flame (water molecule absorption on SiO_2 particles); OH ion indiffusion from the jacketing tube during elongation; same mechanism during fiber drawing. Therefore, dehydration is a must. Figure 4.13 shows a muffle-type carbon resistance furnace in which both dehydration and consolidation is performed. Dehydration is accomplished by $SOCl_2$ via the two reactions /Sudo et al. 1978/

$$SOCl_2 + H_2O \rightarrow SO_2 + 2HCl$$

$$SOCl_2 + Si-OH \rightarrow SO_2 + HCl + Si-Cl$$

at temperatures of $900 - 1350^{\circ}C$. Total dehydration time for several cycles amounts to about 90 min. Slow dehydration at $T < 1150^{\circ}C$ is prefered over the fast/high temperature alternative. At higher temperature the pores tend to close (start of consolidation) with concurrent trapping of OH impurities. It is possible to reduce the OH content to well below 0.1 ppm, if ample $SOCl_2$ is flowing. Gaseous Cl_2 can replace $SOCl_2$.

Consolidation: The whitish soot preform turns into the transparent preform by this process step. Shrinkage is to about 1/8 of the original volume. As indicated in Fig.4.13, dehydration and consolidation can be performed in the same furnace. For consolidation, He and O_2 gases are flushed into the muffle along with a drying agent (Cl_2, $SOCl_2$) and the temperature is raised to ~ 1550°C.

Helium ensures bubble-free transparent preforms, O_2 prevents GeO_2 vaporization, and the drying agent provides a purifying atmosphere.

Note: The apparatus of Fig.4.13 suggests that soot deposition, dehydration, and consolidation are performed continuously in one machine. Though this is possible, a separation of the porous-preform deposition step and the dehydration/consolidation steps are commonplace in production. Reason is the difficulty to match the deposition speed with consolidation speed for high-quality fibers.

Elongation: The as-grown transparent preform whose outer diameter is some 25 mm is elongated to an outer diameter of approximately 10 mm. This step is necessary, together with overcladding, to adjust the desired core/cladding dimensional ratio. Graded index fiber preforms may consist only of the core material, SM fibers have at least part of their cladding deposited. Elongation is accomplished on a glass-working lathe, where the preform is subjected to an oxy-hydrogen burner. The burner moves in opposite direction to one of the lathe's support which, in turn, travels at correspondingly

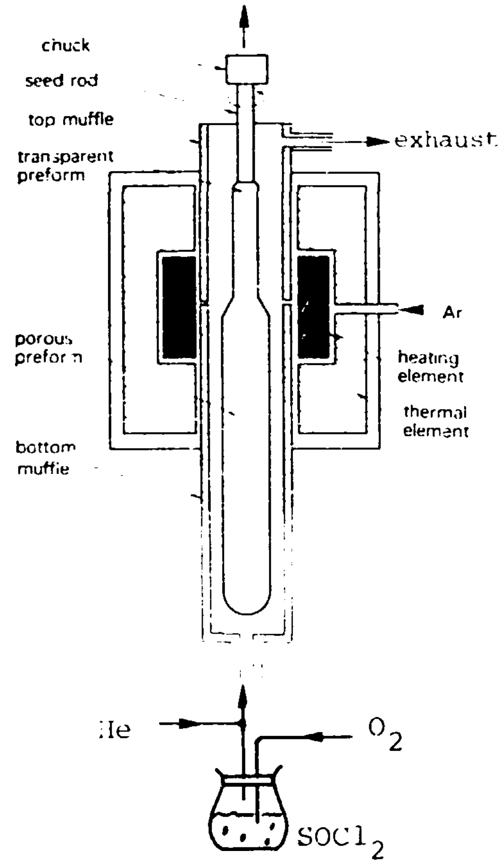


Fig. 4.13: Muffle-type carbon resistance furnace for dehydration and consolidation.

higher speed. Elongation calls for prior cooling, taking-out, and installation of the transparent preform. As a process step it can be omitted - which in fact it has been for the fabrication of absolutely OH-free fibers - if the entire cladding is synthesized simultaneously with the core deposition (no overcladding).

Overcladding: As described in Section 4.3.1. As mentioned, overcladding is usual in the VAD preform fabrication process for GI fibers.

Preform characterization: As described in Section 4.3.1.

4.3.5 Production trends

In the production of hard-glass fiber preforms, which make up the overwhelming share of today's fiber market, several trends can be observed. These trends become evident by patents issued and by publications in scientific journals.

There are rigorous efforts underway to increase productivity which include:

- 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

Other directions at which research is aimed pertain to

- Replacement of P and B as dopants. Boron induces loss at length wavelengths and P-OH groups have been identified as a culprit for gradual increase of attenuation /Uchida et al. 1983/. Fluorine and Al_2O_3 are favorite candidates for lowering or raising the refractive index, respectively.
- Reduction of OH content in general.
- Elimination of the 1.39 µm OH peak (e.g. to facilitate wavelength division multiplex fiberoptic systems).
- 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, Section 4.3.7).

The drawing speed of fiber from preforms is also a limiting production factor. Trends and R & D efforts in this field are discussed in Section 4.5.

It is interesting to note that work on direct glass fiber drawing from the melt has been discontinued in many major laboratories. One reason is that long wavelength operation of such fibers is hampered by water and boron absorption. The stringent requirements on purity of starting material is also an impediment to large scale production of high-quality fibers.

4.3.6 Comparison of CVD processes

First, the general advantages and drawbacks for each process are listed. Then, an attempt is made to compare productivity data. Because of their proprietary nature, no exact figures are available. Of various values given for one process that ones that are actually achieved in production (not champion values for laboratory quantities!) have to be considered. The typical data of produced fibers are also given.

MCVD

Advantages/Potential

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

Limitations/Problem areas

- discontinuous process
- requires high-grade silica substrate tube
- very low GeO_2 deposition efficiency (10 - 20%)
- length taper of index profile (addition of p as remedy is not advisable, see Section 4.3.5)
- central dip of index profile
- preform size limited (fiber length)
- silica tubes necessary

It is estimated that a total of 1500 - 2000 man years 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.

Depending on the quality requirements, from 10% up to 50% of the preform are not used for fiber production due to the length taper problem. High deposition rate versions of the process are suitable for SM fibers only. This is particularly true for the RF plasma-enhanced MCVD process, which is also well suited for high NA fiber production.

PCVD

Advantages/Potential

- 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

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

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

OVPO

Advantages/Potential

- good profile control
- no collapsestep 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

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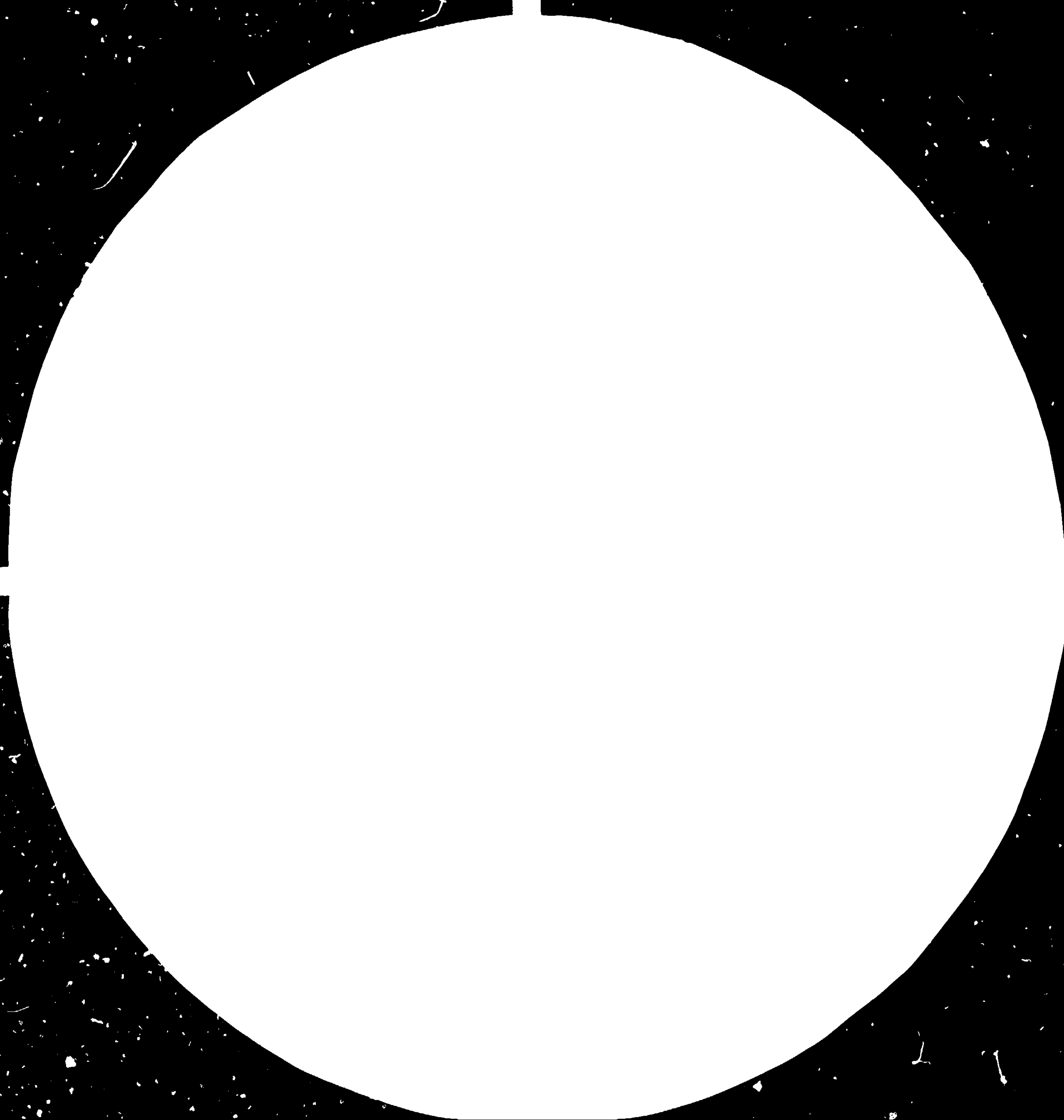

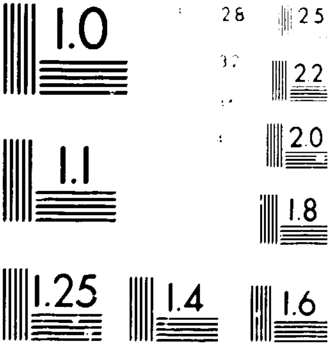
1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

Limitations/Problem areas

- drawing with central hole requires control of atmosphere
- built-in stress of preforms (yield?)
- high NA fibers
- control of deposition complex

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

A specific problem in fabricating multimode fibers in using the OVPO process is that of preform fracture due to thermal shock.

VAD

Advantages/Potential

- 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

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

Approximately 1000 man years have been consumed by development of this process. For high-quality fibers, the potential of a continuous process are presently not exploited (separate deposition and consolidation steps). Silica substrate tubes are used presently for overcladding, but their availability is not essential for the process. It requires dehydration but yields low OH content fiber.

In any CVD technique, transition metal ion impurities are generally no problem. Temperature control to approximately within ±2°C is necessary for optimum results. Accurate control of gas flow is also common to all processes. Data on yield decrement due to breakage of preforms. For the comparison of economics, simple comparison of deposition rates is not sufficient. Additional cladding of prefabricated tubes reduces the total volume of deposited material necessary. The flexibility to produce all kinds of fibers today in use has been demonstrated for all processes. A possible exception are high NA fibers, which require a large core and high GeO_2 deposition efficiency. The influence of deposition efficiencies on relative material cost contribution to fiber price is shown in Table 4.2 /Koel 1983/. Concerning dopants, fluorine incorporation has been demonstrated in all four processes, but seems to be easier implemented at present for MCVD and PCVD. Many layered deposition (OVPO, PCVD) is advantageous for good profile control and, hence, high bandwidth of GI fibers. MCVD seems to have the least potential for further improvement of process control and productivity.

4.3.7 Sol-gel process

A glass preform fabrication method entirely different from CVD is the sol-gel process /Susa et al. 1982, Satoh et al. 1983/. 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

Table 4.1: Comparison of data affecting productivity of CVD processes.

	MCVD		PCVD[2]	OVPO	VAD
		RF-MCVD		(OVD)	
Number of layers	30 - 100	20	500 - 1000	~1000	not applicable
Deposition rates[1]	0.5 - 1 g/min (2.3 g/min)	~3.5 g/min (5 g/min)	0.5 g/min (1.3 g/min)	1 - 4 g/min (6 g/min)	1 - 4 g/min
Deposition efficiency SiO_2	40 - 70%	80%	almost 100%	50%	60 - 80%
Deposition efficiency GeO_2	10 - 20%	80%	70 - 90%	?	?
Time for making preforms[3]	~7 h/10 km preform[4]		~4 h/8 km preform		~6 h/10 km preform

[1] Typical rates in present-day production are given. Number in parenthesis give champion values achieved in the laboratory.

[2] Koel 1982

[3] For 50/125 um fibers

[4] Nagel et al. 1982

Table 4.2: Material cost of various fibers relative to 100% deposition of both SiO_2 and GeO_2 for a 50 µm/125 µm GI fiber (NA = 0.2) /Koel 1983/.

Efficiency of deposition GeO_2	Efficiency of deposition SiO_2	GI fiber 50/125 µm	SM fiber 125 µm	GI fiber 100/140 µm NA = 0.3
100%	100%	100	93	108
85%	100%	101	93	112
50%	100%	104	93	123
50%	50%	109	98	147
20%	50%	134	98	221
10%	50%	146	99	343

cylindrical glass containers; (ii) drying of the gel to form a porous gel body (one week at 70°C); (iii) a chlorination process to reduce the initially high (~1000 ppm) OH content; (iv) sintering of the porous gel body (apparent density = 1.1 g/cm^3) to produce a transparent glass preform.

The last step is preformed at only 1100°C under a He atmosphere to form a pore-free glass. The main advantages of this method are:

- low-temperature
- potential of mass production.

The process has been used so far in the laboratory only.

4.4 Fiber drawing

The preforms fabricated by any of the just-mentioned processes are now drawn into the actual fibers. Prior to drawing, preforms should be etched or, better, fire-polished to eliminate surface effects that degrade fiber strength. Several fire polish runs at 1700 - 1900°C are made with a final one at lower temperature (1400°C) for annealing. The drawing process includes several separate operations, all of which have to be carefully controlled /Blyler and DiMarcello 1980/.

- 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.

Figure 4.14 shows a schematic of a fiber drawing tower, with reference to which the apparatus and process steps will be discussed.

Heat source: The heat source has to be capable of achieving 2200°C with ±2°C temperature stabilization to melt the silica fiber preforms. Temperature is monitored by a pyrometer whose output is used to control furnace heaters. Two types of furnaces are presently in general use. Zirconia induction furnaces consist of ring - shaped RF susceptors driven by 4 MHz RF power generators. No protective gas is needed, but the furnace must be relatively tight at the preform input/fiber output ports to provide a still atmosphere. The other type of furnaces are graphite, directly-heated. Such furnaces are cheaper but the heater element must be changed periodically. The problem is not so much the price of this element, but rather the need for temporary apparatus shut-down. In any

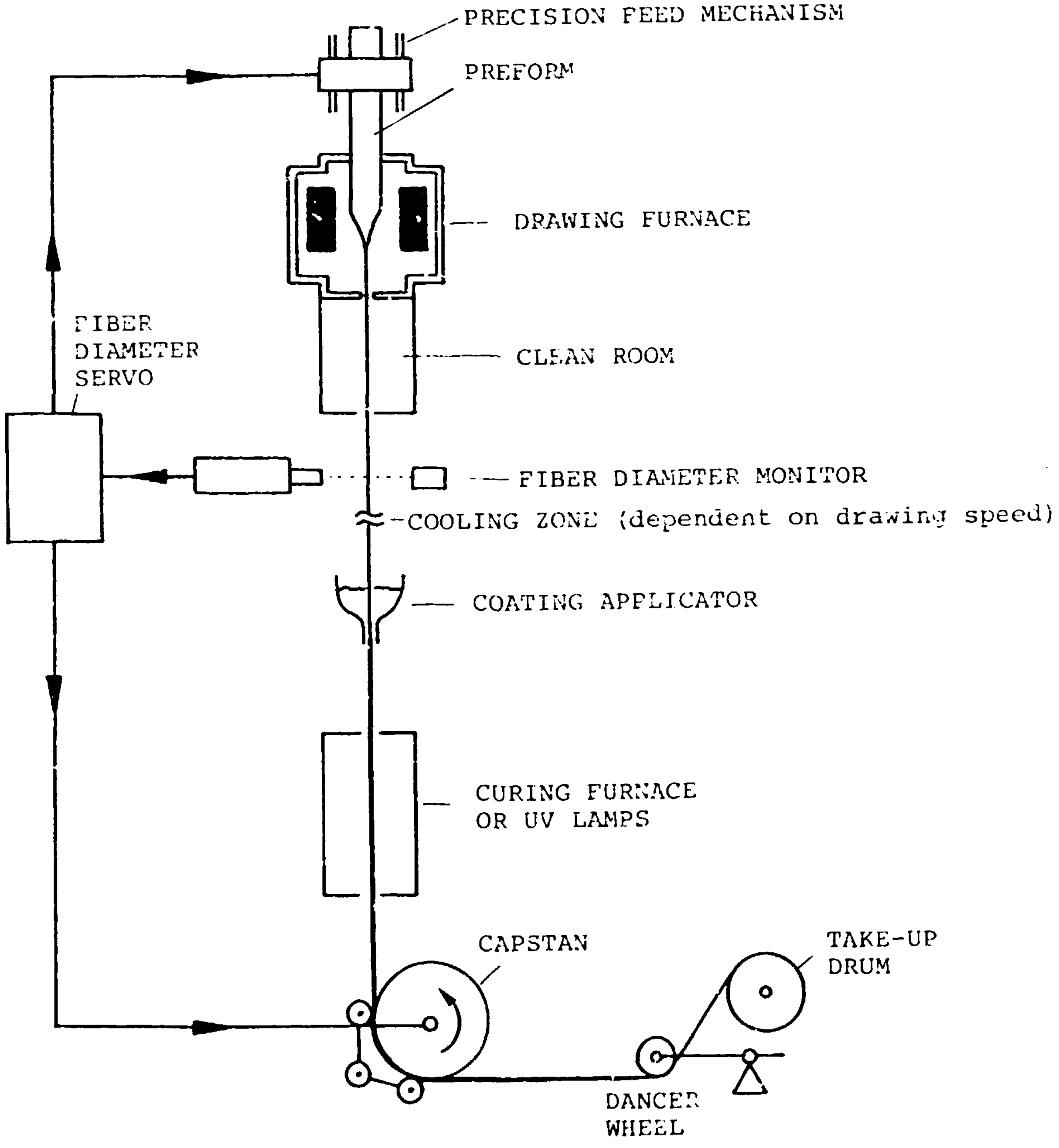

Fig. 4.14: Schematic of fiber drawing tower.

case construction must ensure that no particulate matter or vapors from the furnace materials can adhere to the fiber. Argon or nitrogen is usually flushed to prevent burn-off of furnace materials.

Clean room conditions: Particles fusing to the fiber before coating dramatically decrease eventual fiber strength. Some manufactures have found it beneficial for fiber yield to provide a clean-room atmosphere to the pristing glass fiber before it is coated (Class 100). The critical location extends from just below the furnace (fiber temperature ~1600°C) to the (first) coating cup (fiber temperature 60 - 80°C). Depending on drawing speed this length where the fiber is exposed to ambient air is from 0.8 to 4 m (drawing speed 1 - 5 m/sec, respectively) /Paek and Schroeder 1981/. In general, the atmosphere in rooms where fibers are drawn are clean-room Class 1000 or 10000.

Fiber diameter monitor: Fiber diameter is monitored by a He-Ne laser forward scattering diameter measuring system (resolution and accuracy: 0.1 - 0.25 µm). A servo driven by this monitor's signal controls both the precision feed mechanism of the preform and the take-up speed of the drawn fiber. This part of the system provides dimensional control of the fiber.

Coating: To protect the vulnerable glass fiber and to preserve its inherent strength, a primary coating is applied right after drawing. This step is described in detail in the following Section.

Fiber take up: A presision-drive capstan (diameter of the order of 30 cm) provides uniform and defined tension to pull off the fiber. Typical values are 20 - 50 g tension on the bare fiber. An optional dancer wheel serves to keep tension constant. The fiber is then taken up on a metal or plastic drum of approximately 20 - 40 cm diameter.

4.5 Coating

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

- fiber strength
- fiber loss (microbending)

Failure of glass fibers usually results from surface flaws or stress concentration. Therefore, the fiber should be coated as early as possible in the drawing stage. Coatings also give additional strength to the fiber by taking some of the applied stress.

Excess fiber loss is often associated with improper coating techniques /Blyler and DiMarcello 1980/. To avoid lumps and voids in the coating and even uncoated sections,

- viscosity of the liquid coating material has to be optimized;
- geometry of the coating cup has to be optimized;
- materials free from particulate matter have to be used;
- a particulate-free atmosphere during drawing has to be maintained;
- premature curing of the coating material has to be prevented.

Coating 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. Instead of applying the coating in one layer, several-layered coatings, each separately cured, facilitate dramatic increase in drawing speed. The previously mentioned distance between furnace and coating die determines the height of the drawing tower. Towers as high as 17 m have been built, but recent developments go to smaller towers with the fiber being run up and down over several rolls between multiple coating steps.

Two different coating systems are in wide use. One uses materials staying compliant after curing. This soft coating buffers stress to keep microbending of the glass fiber low ("primary coating"). Pressurized dies have recently facilitated considerable coating and, hence, drawing speed increases /Chida et al. 1982c/.Primary coating is usually applied in two layers: one of modified, expensive silicone immediately on the fiber, the other one of not-so-critical silicone material. Poor abrasion resistance dictates additional application of a tough jacket, usually nylon ("tight jacket"). This jacket, sometimes called "secondary coating", tightly fits around the primary coating(s) and has a diameter of 0.8 to 1.0 mm. The other system applies one or two layers of acrylates. High-power UV lamps cure the acrylate(s) on the just-drawn fiber. AT & T Bell Laboratories have achieved drawing speeds of 12 m/s on an experimental drawing tower, but lower speeds are standard. As glass is UV sensitive, maximum usable UV power is limited. Such fiber are usually protected against outward influence either by a hollow plastic tube ("loose jacket") or they are directly placed in slots of cylindrical plastic member of the optical cable ("slotted-core cable"). Table 4.3 gives an overview of the technical details of coating. Choice of either system seems to be more a question of belief and tradition than of technical superiority. For details and consequences on cabling process see Chapter 5.

Table 4.3: Comparison of coating systems /Koel 1983/, reproduced with permission.

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

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1) Numbers in parentheses are laboratory results.

4.6 Plastic-clad silica fibers (PCS fibers)

PCS fibers are designed as SI fibers, i.e. the silica core has uniform refractive index. The cladding is a relatively low-loss polymer with a lower refractive index. This index difference can be chosen large so that high NA fibers result.

Starting material is a silica rod of desired purity which determines the lower limiting loss value. Natural quartz is a popular choice. Phosphorus or boron may be added to lower the rod's melting temperature.

A chemical etch and a fire polish remove impurity centers at the future core/cladding interface. Then the fiber is drawn as described in Section 4.4.

The cladding is preferably applied by the methods of Section 4.5, which requires a curable liquid as cladding material. It is usual to use two layers of cladding: a soft first coating and a high-modulus second one. Hardeners mixed with the liquid coating speed up the curing process and fabrication of fiber. Exact composition of cladding materials is proprietary, but the following systems have been published /Grabmaier et al. 1977, Kaiser et al. 1975, Tanaka et al. 1975/

- silicone resins (e.g. cross-linked polysiloxane)
- perfluoronated ethylene propylene (FEP)
- polymethacrylate (partially fluoridized)
- polyalkene (fluoridized)

The selection of a suitable cladding is guided by the following considerations:

- low optical loss (of bulk material)
- availability in high purity form
- adhesion to silica

- high strength of resulting fiber
- ease of cladding procedure

Alternative methods of cladding include the extrusion of a molten polymer in an extruder crosshead /Kaiser et al. 197 /. This cladding procedure, however, seems to be more involved and more difficult to control.

It should be noted that raw materials from different manufacturers exhibit different optical loss.

4.7 Drawing from the glass melt

For this fiber production method, a high-purity glass melt has to be prepared. As described in great detail by /Midwinter 1979/, the following steps and methods are involved.

Glass forming powders (SiO_2, B_2O_3, GeO_2, ... Na_2CO_3, K_2CO_3, $CaCO_3$, $BaCO_3$, ...) which are premixed are heated in a crucible until they fuse and are agitated to form a homogeneous mix. (Table 4.4 /Beales et al. 1980/ gives an impression of popular glass systems.) The heat melting can be imparted directly to the glass (e.g. by 5 MHz RF induction coil) or to a highly purified crucible, either by direct electrical heat or by RF (~100 kHz), if the crucible is made from metal. Platinum is a suitable metal for the latter kind, cheaper and easier obtainable crucibles are made from silica. These can only be used once because the glass constituents partly dissolve the silica.

After initial heating the melt has to be stirred for homogenization by a platinum or ceramic stirrer. Additives like oxides of arsenic and antimony exert control of impurities by redox processes.

Glass rods are pulled from this purified melt for storage and subsequent use.

Producing the actual fiber is done by a <u>double-crucible</u> apparatus (Fig.4.15). Two concentric crucibles with vertical axes, preferably made from Pt end at their bottom in a central circular nozzle.The inner nozzle, feeding the core melt, is carefully aligned concentric within the outer nozzle and positioned about 1 cm above, supplying the core material. The core material exudes into the space below the outer crucible nozzle, where it is surrounded by the cladding melt. A filament of core cladding fiber is pulled from this lower end tip.

Table 4.4: Composition and performance of SI fibers made by the double-crucible method /Beales et al. 1980/.

Core glass	Cladding glass	Numerical aperture	Loss (dB/km)
$Na_2O-B_2O_3-SiO_2$	$Na_2O-B_2O_3-SiO_2$	0.18	3.4
$Na_2O-Li_2O-CaO-SiO_2$	$Na_2O-Li_2O-CaO-SiO_2$	0.23	4.2
$Na_2O-CaO-SiO_2$	$Na_2O-CaO-SiO_2$	0.26	5.2
$P_2O_5-Ga_2O_3-GeO_2$	$P_2O_5-Ga_2O_3-SiO_2$	0.3	8.5
$Tl_2O-Na_2O-B_2O_3-GeO_2-BaO-CaO-SiO_2$	$Na_2O-B_2O_3-SiO_2$	0.3	12
$Na_2O-BaO-GeO_2-B_2O_3-SiO_2$	$Na_2O-B_2O_3-SiO_2$	0.32	7.2
$Na_2O-BaO-GeO_2-B_2O_3-SiO_2$	$Na_2O-B_2O_3-SiO_2$	0.43	9.8
$Na_2O-BaO-GeO_2-B_2O_3-SiO_2$	$Na_2O-B_2O_3-SiO_2$	0.50	12
$Na_2O-BaO-GeO_2-B_2O_3-SiO_2$	$Na_2O-B_2O_3-SiO_2$	0.6	15
$Na_2O-B_2O_3-SiO_2-GeO_2$	-	0.53	20

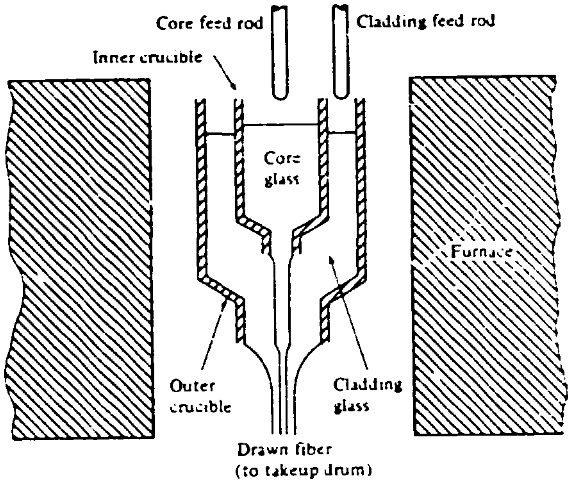

Fig. 4.15: Schematic of fiber drawing apparatus by the double-crucible method.

Reproduced with permission: G.Keiser, Optical Fiber Communications, McGraw Hill, 1983.

Advantages of this approach are the basic simplicity to produce an optical fiber, that it is semicontinuous and that low-melting-point glasses are used. The disadvantages result from the fact that contamination is difficult to control. The starting materials have to have already the final degree of purity. Highly refractory and expensive materials such as Pt have to be used. The gaseous atmosphere surrounding the double crucible must be carefully controled. Finally, index profiles have been obtained for fibers made by the described process, but control of diffusion and of uniformity along the fiber length are extremely difficult.

Work on the double crucible method has been discontinued in most major laboratories, but low-cost moderate-performance fibers are made in this way by several manufacturers. The process seems advantageous for SI fibers with high NA.

4.8 Plastic fibers

The selection criteria of materials suitable for plastic optical fiber production have been listed in Section 4.6. Popular core/cladding combinations are /Keiser 1983, NTT 1983/:

core	cladding	NA
polystyrene - PS $n = 1.60$	poly-methyl-methacrylate - PMMA $n = 1.49$	0.6
PMMA $n = 1.49$	fluorinated alkyl-meth-acrylate copolymer $n = 1.40$	0.5

Fabrication steps include

- monomer distillation
- washing of polymerization vessel with distilled monomer
- polymerization of core material
- drawing
- cladding with molten polymers

A state-of-the-art apparatus is shown schematically in Fig.4.16 /NTT 1983/. The actual fiber drawing is by a method similar to the double crucible process. The key to obtain low-loss fibers (55 dB/km at selected wavelengths) is the use of a completely closed system, which is necessary to avoid dust, oxygen and other contaminants to become included in the fiber. Another important step toward lower loss is partial deuterization of the PMMA used for the core /Beasley et al. 1979/. Exact production details are not available from the largest and, by his own claim, sole large-scale producer (Mitsubishi Rayo) of PMMA fiber.

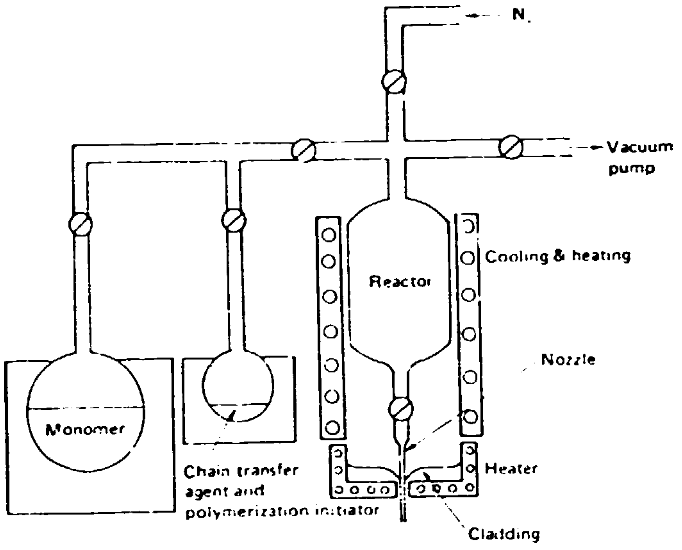

Fig. 4.16: Schematic of polymerization and fiber drawing apparatus for low-loss PMMA fibers /NTT 1983/, reproduced with permission.

5. PRODUCTION OF OPTICAL CABLES

This chapter is concerned with the conversion of the fibers discussed in the previous chapter into practical cables which can be handled in the same way as conventional electrical transmission cables. But fibers cannot be handled straight-forwardly like copper wires, since, compared with metal, glass fibers differ considerably in the mechanical properties. The 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. As a result of the low optical losses which have been achieved in the basic fibers, considerable attention has to be paid to minimizing additional losses which might be introduced during cable-making and installation or, after installation, by environmental and mechanical factors.

5.1 Mechanical fiber properties

Strength and static fatigue are the two basic mechanical characteristics of glass optical fibers. Since the sight and sound of shattering glass are quite familiar, one intuitively suspects that glass is not a very strong material. However, the longitudinal breaking stress of pristine glass fibers is comparable to that of metal wires. The cohesive bond strength of the constituent atoms of a glass fiber governs its theoretical intrinsic strength. Maximum tensile strengths of 14 GPa have been observed in short-gauge-length glass fibers. This is close to the 20 GPa tensile strength of steel wire. In practice the existence of stress concentrations at surface flaws or microcracks limits the median strength of long glass fibers to the 700 to 3500 MPa range. The difference between glass and metal is that, 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. The primary cause is erosion by the presence of water in the environment which reduces the strength of the SiO_2 bonds in the glass. The speed of the growth reaction is increased when the fiber is put under stress. However, based on experimental investigations, it is generally believed (but not yet fully substantiated) that static fatigue does not occur if the stress level is less than approximately 20 percent of the maximum strength in a dry environment, such as a vacuum. Certain fiber materials are more resistant to static fatigue than others, with fused silica being the most resistant of the glasses in water. In general, coatings which are applied to the fiber immediately during the manufacturing process afford a good degree of protection against environmental corrosion.

Another important factor to consider is dynamic fatigue. When an optical cable is being installed in a duct, it experiences repeated stress owing to surging effects. The surging is caused by varying degrees of friction between the optical cable and the duct or guiding tool in a manhole on a curved route. Varying stresses also arise in aerial cables that are set into transverse vibration by wind /Keiser 1983/.

5.2 Fiber jacketing

Now we will turn to the problem of jacketing the fiber in such a way that the fiber is sufficiently protected to be incorporated into cables. 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 the packaging two philosophies have been developed:

- 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. The tensile effect is based on the principle of load sharing between the fiber and the plastic coating. Adequate mechanical protection is obtainable with nominal coating diameters in the range 0.8-1 mm. A number of high modulus plastics have been used for secondary coatings, including amorphous polyethylene terephtalate (polyester), polypropylene, and nylons /Sandbank 1980/. These can be applied by thermoplastic extrusion using a small conventional wire insulating line. The techniques of extrusion and for cooling the extruded product in water have to be closely controlled to avoid degradation of the optical transmission properties of the fiber due to stresses in the fiber caused by thermal contraction or morphological changes in the plastic. After cooling down a drum takes up the now basically cabled fiber with defined tension. This tension has to be matched to the expected shrinkage of the jacketing material. An excess loss induced by this jacketing method can be kept well below 0.1 dB/km at $\lambda = 1.3$ µm. For easy identification during installation and repair the jacket may be color-coded.

- 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 the cables 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. As shown in Fig.5.1(a), each fiber is individually protected by a small plastic tube (typical diameter is 1.4 mm) filled with a water-blocking jelly. The inner diameter of the tube is much larger than the 250 µm-diameter of the primary-coated fiber. For the loose-tube jacketing only UV curable acrylates can be used since this material ensures low friction of the fiber inside the tube. Usually the coating is applied as two separate layers with the second layer color-coded. The fiber being somewhat longer than the tube takes up the configuration of a long-pitch helix. In the case of a change in the tube length by tension or temperature the pitch length changes. The percentage of the excess fiber length has to be chosen very carefully. As Fig.5.2 demonstrates, losses due to microbending occur already in the unstressed state, if the fiber is too long and the helix pitch is too short. If the fiber is too short, the loss increases already at weak cable strain. Figure 5.3 compares loss increase $\Delta\alpha_E$ and strain of the cable and fiber, respectively, as a function of tensile force F of a loose-tube cable with a tight-fit cable. It demonstrates the decoupling of fiber from strength member for the loose tube.

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, according to Fig.5.1(b), by an extruded loose-fit plastic tube. This tube has typically an outer diameter of 3 mm. The remaining space is filled with a jelly.

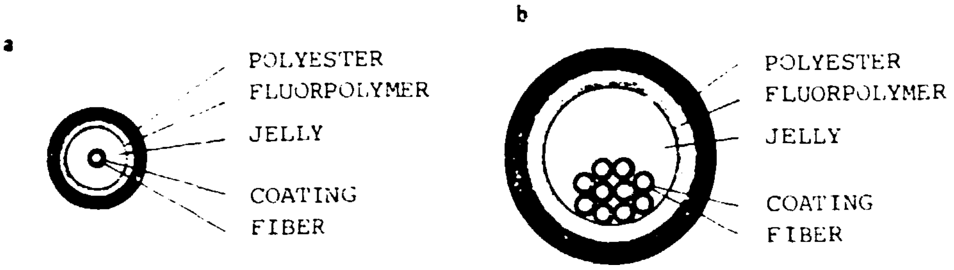

Fig.5.1: Cross section (scale 10:1) of the loose-tube jacketing
(a) for a single fiber
(b) for a bundle of 10 fibers /Oestreich 1983/, reproduced with permission.

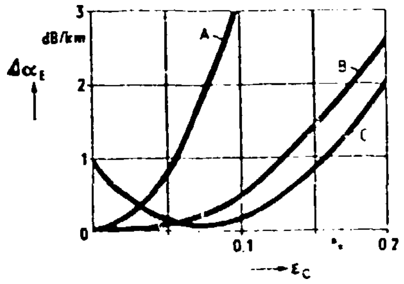

Fig.5.2: Loss increase $\Delta\alpha_E$ of the fiber as a function of the cable elongation ε_C for different amounts of fiber slack
A: slack too less
B: slack normal
C: slack too much
/Rosenberger 1982/, reproduced with permission.

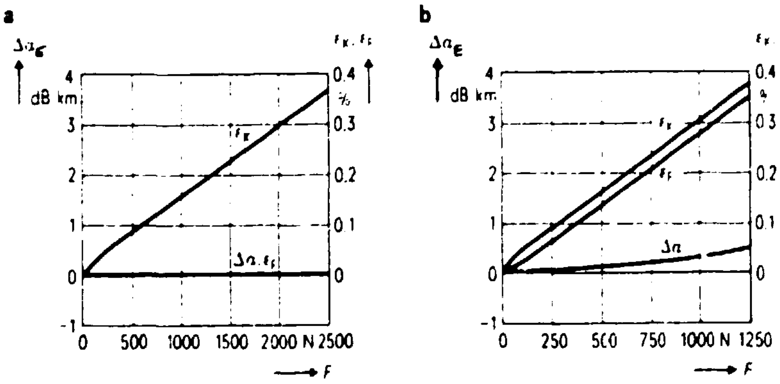

Fig.5.3: Loss increase $\Delta\alpha_E$ and strain of cable and fiber, respectively, as a function of tensile force
(a) for a cable with loose-fit tubes
(b) for a cable with tight-fit jackets /Sutor 1983/, reproduced with permission.

Both constructions, loose-tube and tight-fit jacketing, have inherent advantages. The loose-tube construction offers 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 designs for a similar fiber configuration and generally yields a more flexible, crush resistant cable. A trade-off between these structures is shown in Table 5.1.

Table 5.1: Trade-off between loose-fit and tight-fit jacketing.

Cable Parameter	Cable Structure	
	Loose Tube	Tight Jacket
Bend Radius	Larger	Smaller
Diameter	Larger	Smaller
Tensile Strength	Higher	Lower
Impact Resistance	Lower	Higher
Crush Resistance	Lower	Higher
Microbending Sensitivity	Lower	Higher
Attenuation Change At Low Temperatures	Lower	Higher
Splicing	More Sophisticated Equipment	Easier
Requirements On Jacketing Control	Lower	Higher

5.3 Cable design principles

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. They ensure that fiber elongations are limited to 0.1 to 0.2 percent /Keiser 1983/. The cable structures in which one fiber or even more than hundred fibers are incorporated 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).

Different cable designs are required for each type of application, but certain fundamental cable design principles will apply in every case.

5.3.1 Strength members

One important mechanical property is the maximum allowable axial load on the cable since this factor determines the length of cable that can be reliably installed. 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. In principle all the cable components add to its tensile strength. However, with limitations imposed on the strain by the optical fibers, it is normally advantageous to include a component specifically to increase the effective tensile strength without unduly stiffening the cable.

Tensile strength is of special importance in long cables (for example, cables installed in ducts) where the tension required for pulling increases throughout the process as a function of the coefficient of friction between the cable sheath and adjacent surfaces. For straight ducts the tension increases linearly with the length, but for curves in ducts an additional exponential increase occurs which can substantially raise the pulling-in tension. A figure of merit for tensile properties is provided by the ratio of the tension at a standard strain to the weight per unit length: this applies to individual components as well as to the completed cable. Preferred features of a strength member are therefore:

- high Young's modulus,
- low weight per unit lenght,
- flexibility to minimize restriction of the bending capability of the cable.

Other features that may be relevant include friction against adjacent components, transverse hardness, and stability of properties over a range of temperatures including those encountered during cable manufacture and in service.

5.3.2 Stranded strength members

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, a phenomenon commonly observed in fibers subject to localized mechanical stress.

5.3.3 Strength member materials

Five main types of material have been proposed or employed for the construction of strength members on account of their high Young's moduli: steel wires, plastic monofilaments, multiple textile fibers, glass fibers, and plastics reinforced with glass or carbon fibers (FRP). Some significant features of these materials are summarized below:

- Steel wires: These have been widely used in conventional cables for armoring and longitudinal reinforcement. Various grades are available with tensile strengths to break ranging from 540 to nearly 3100 MPa. All have the same Young's modulus (19.3×10^4 MPa) and the choice is guided by the preference for a high strain at yield compatible with that of optical fibers. The main disadvantage of steel is its high specific gravity which substantially adds to the cable weight.

- Plastic monofilaments: This type of strength member is available commercially in several basic materials and is of particular interest where low weight or freedom from metals are prime requirements for the cable, but is not technically competitive with steel for cables to be installed in long ducts (more than 500 m).

- Textile fibers: Commercial forms normally consist of assemblies of many small diameter fibers laid up in twisted or parallel configurations. Typical examples in conventional cables are polyamides (nylon) and polyethylene terephthalate ("Terylene", "Dacron", etc.), with elastic moduli which may be as high as 1.5×10^4 MPa for the individual fibers. Owing to the large number of individual fibers they are resilient in a transverse direction and are useful as cable fillers and binders as well as providing improved tensile properties in optical fiber cables. But they are more bulky than monofilaments of equivalent strength. An exceptional member in this class which has been widely employed in optical cables is "Kevlar" (a trademark of Du Pont), an aromatic polyamide. The individual fibers have the exceptionally high modulus (for an organic material) of up to 13×10^4 MPa which, coupled with its specific gravity of 1.45, gives it an effective strength-to-weight ratio nearly four times that of steel. Commercial forms of Kevlar suitable for cable reinforcement consist of composites of large numbers of single filaments assembled by twisting, stranding, plaiting and/or resin bonding, and retain a high portion of the single fiber modulus.

- Glass fibers: For some applications the optical fibers may supply sufficient tensile strength, but additional nonactive fibers can be used, generally in a manner similar to textile fibers, if higher strength is required. Elastic modulus is high, typically 9×10^4 MPa, but the elongation to break may deteriorate to an unacceptably low value. Silica fibers are included under this heading, and when protected by online plastic coating have superior properties and greater stability compared to those of multicomponent glasses.

- Fiber reinforced plastics (FRP): Plastic materials are combined with either glass or carbon fibers. These reinforced materials have been successfully employed in rigid and semirigid plastic or metal composites, and have a modulus of up to 20×10^4 MPa in single filaments.

Table 5.2 contains relevant properties of these materials.

Table 5.2: Properties of strength member materials /Kao 1982/.

Materials	Specific Gravity g/cm^3	Young's Modulus, MPa	Tensile Strength, MPa	Strain at Break, %	Normalized Modulus-to-Weight Ratio	Expansion Coefficient
Steel wire	7.86	19.3×10^4	$5-30 \times 10^2$	2-25	1.0	1.2×10^{-5}
Polyester monofilament	1.38	$1.4-1.6 \times 10^4$	$7-9 \times 10^2$	6-15	0.3	1.3×10^{-4}
Nylon yarn	1.14	$0.4-0.8 \times 10^4$	$5-7 \times 10^2$	20-50	0.3	7.2×10^{-5}
Terylene yarn	1.38	$1.2-1.5 \times 10^4$	$5-7 \times 10^2$	15-30	0.3	1.4×10^{-5}
Kevlar-49 fiber	1.45	13×10^4	30×10^2	2	3.5	-1.1×10^{-6}
Kevlar-29 fiber	1.44	6×10^4	30×10^2	4	1.6	-1.1×10^{-6}
S-glass fiber	2.48	9×10^4	30×10^2	3	1.4	1.9×10^{-6}

Besides the strength, the weight, and the elongation limit, the expansion coefficients and the cost of the strength members are equally important. The strength, the weight, and the elongation limit govern the cable size necessary to meet the strength specification. The expansion coefficient influences the cable structural design since a high expansion coefficient relative to the fiber could cause significant fiber distortion within the cable structure over a temperature range while a low expansion coefficient could help to prevent fiber distortion.

5.3.4 Lateral fiber protection

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 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 position of the strength members can be the center of the cable (Fig.5.4a) or the strength members can be placed around the fibers (Fig.5.4b). Both systems have specific advantages. A centrally located strength member provides maximum flexibility, but if placed around the fibers it may protect them from radial crushing forces. A special design is necessary for self-supporting aerial cables, which are installed on poles or additionally between power transmission towers. Steel strands (Fig.5.5a) or, if a non-metallic design is advantageous, FRP rods (Fig.5.5b) are incorporated in the non-symmetric cable. The combination of strength member and optical fiber cable can be continuous over the complete cable length, but sufficient performance over a wider temperature range is given by a cable type, in which the optical cable is bound with a lashing wire or clamps to a messenger wire at certain distances; however, at cost of ease of installment.

5.3.5 Summary of cable design objectives

Similar to insulated copper wires the tight-fit jacketed fiber as well as the loose-fit tube containing one or several fibers can be regarded as unit member for further manufacturing in conventional cable stranding machines. A large variety of structures are possible, but should be based on the principal considerations to designing a fiber cable summarized as follows:

- Maximum strain allowed on the fibers during the cable fabrication process, installation, and service. This determines the minimum strength of the fiber to be used in the cable structure and the amount of strength member required.

- Maximum static and dynamic lateral forces exerted on the fiber. This determines the packaging configuration and the microbend tolerance limit of the fiber.

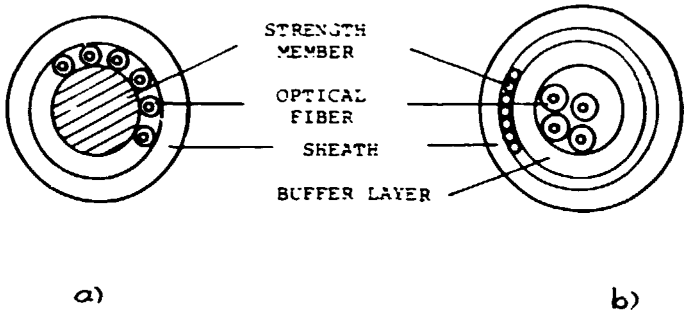

Fig.5.4: Typical constructions used for optical fiber cables.
(a) Inner strength member
(b) Outer strength member.

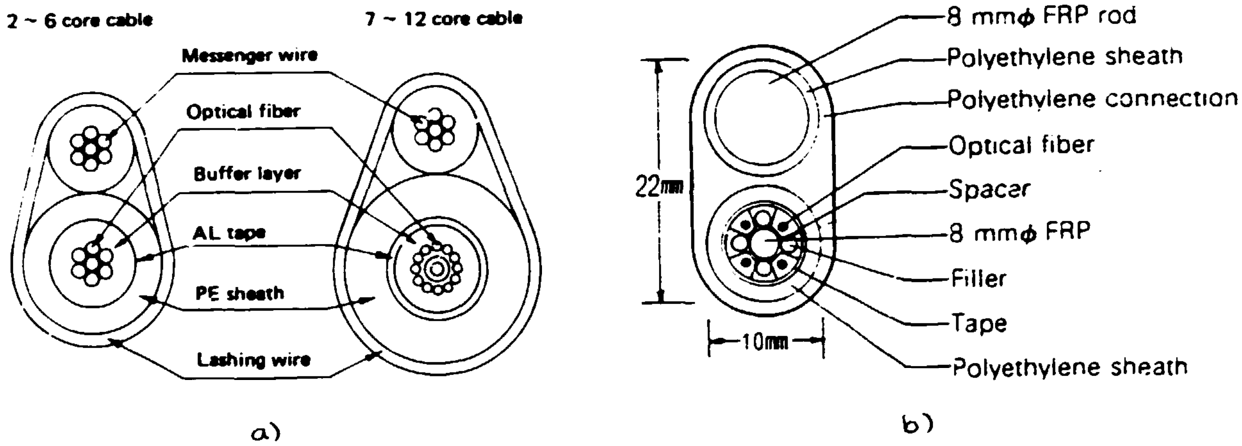

Fig.5.5: Self-supporting aerial cables with steel wires (a) or FRP rods (b) as strength members /Sumitomo 1984/.

- Adequate flexibility. This requires the fibers to be laid in a helix. It is to be noted that fibers are elastic and hence must be laid with uniform tension in order to achieve lay uniformity.

- Temperature range and environment over which the cable operates. This determines the type of materials to be used, particularly in terms of their thermal expansion coefficient and dimensional change with moisture content.

These design objectives lead to the following important design directions:

- Avoid appreciable loading of fibers
- Isolate fibers from other cable components (long mechanical coupling length)
- Keep fibers close to neutral axis or provide space for them to move
- Design outer sheath to protect against external environment
- Choose cable materials to minimize differential thermal expansion of cable components
- Unit-based cable design - this eases handling and splicing

Similarly, appropriate manufacturing directions can be identified:

- Only use fibers with a specified minimum strength
- Minimize fiber loads during cable manufacture

5.4 Optical cable designs

Many cable structures have been developed on both loose and tight configurations. The simplest 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. Figure 5.6 depicts such a design.

In the telecommunications industry larger cables containing up to thousands of fibers are required. From the large variety of published cable structures we will pick out some examples representing the state of the art. Three different basic cable structures can be distinguished:

- the stranded circular design
- the slotted-core design
- the rectangular array ribbon cable.

In the stranded circular design several basic fiber units (loose tube containing one fiber, or tight-jacketed fiber) are stranded around a central strength member. This is illustrated in Fig.5.7 for a six-fiber cable. The fiber units are bound onto the strength member with paper or plastic binding tape, and then surrounded by an outer jacket. Metallic wires can be included within the cable structure to power repeaters along the route or to act as an engineering order wire for voice communication during cable installation. In a similar manner tubes containing not one but 10 fibers can be arranged around a central strength member increasing the packing density. Figure 5.8 shows such a construction of a 70 fiber cable.

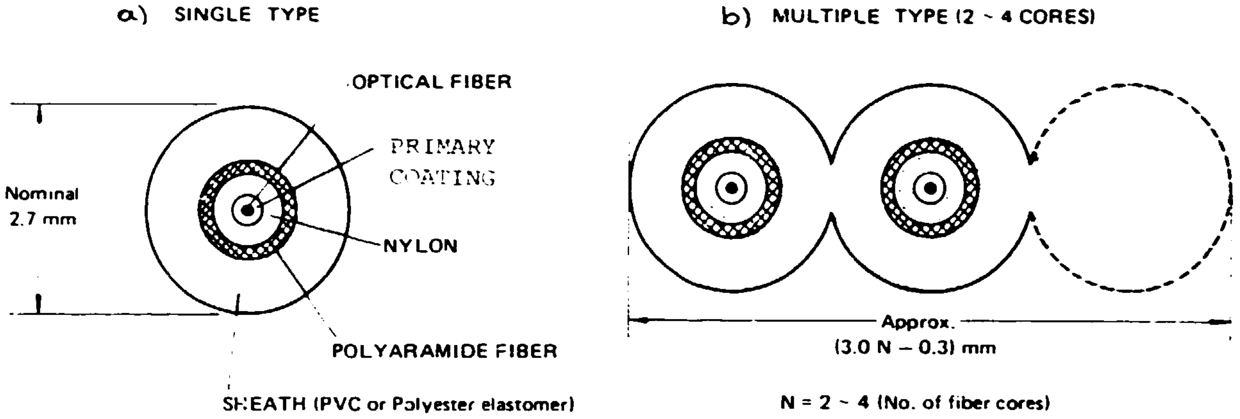

Fig.5.6: Optical fiber cord containing one (a) or up to four (b) optical fibers /Furukawa 1984/.

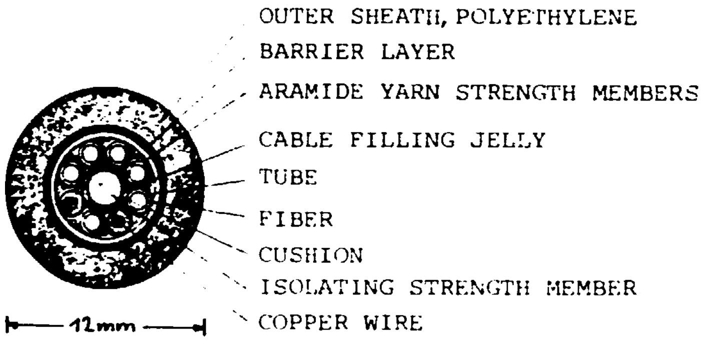

Fig.5.7: Six-fiber cable based on the loose-fit tube containing one fiber as depicted in Fig.5.1(a) /Oestreich 1983/, reproduced with permission.

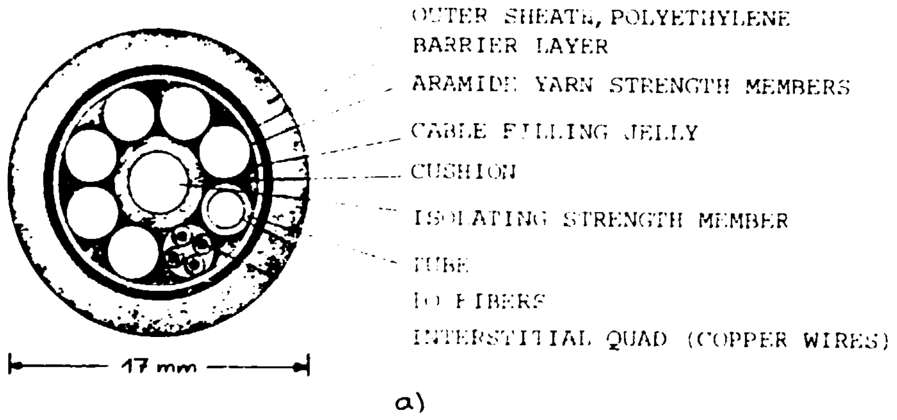

Fig.5.8: Cross section (a) and perspective view (b) of a 70-fiber optical cable based on the loose tube containing 10 fibers /Oestreich 1983/, reproduced with permission.

A high-density cable demonstrating the design flexibility using loose tubes is shown in Fig.5.9. Ten tubes each containing ten fibers are wounded around a strength member. These sub-cables are then arranged in two layers around a central strength member yielding a cable containing 2000 fibers.

Where robustness is all important, or where continual flexing, impacts and crushing may be expected, such as with an under-carpet data dable, tight-buffered fibers are stranded directly into cable form or placed helically around a central strength member. Although this provides increased resistance to impact and crush, the bonding of the fiber to its tight jacket makes the fiber more temperature sensitive. Figure 5.10 shows a typical construction. Figure 5.11(a) shows the cross section of a cable with fibers supported by soft cushions, whereas the cable depicted in Fig.5.11(b) incorporates fully supported fibers.

The slotted-core cable is formed by extruding hot plastic through specially-designed dies and around the strength member. Helically wound slots (typically six to twelve) are formed, where one or more coated fibers run in the void of each slot. Similar to the loose-tube design the fibers are decoupled from the strength member. The slack of the fibers is provided by inserting the fibersin the slots of the support element, which is held under mechanical tension. After applying one or more layers of plastic tape, the support element is detensioned to release the slack of the fibers. A construction developed by Northern Telecom is shown in a perspective view in Fig.5.12.

Besides the structures in which the fibers are arranged symmetrically around a central strength member, rectangular ribbon array cables have been developed. In such a structure, as designed by the Bell Telephone Laboratories, twelve

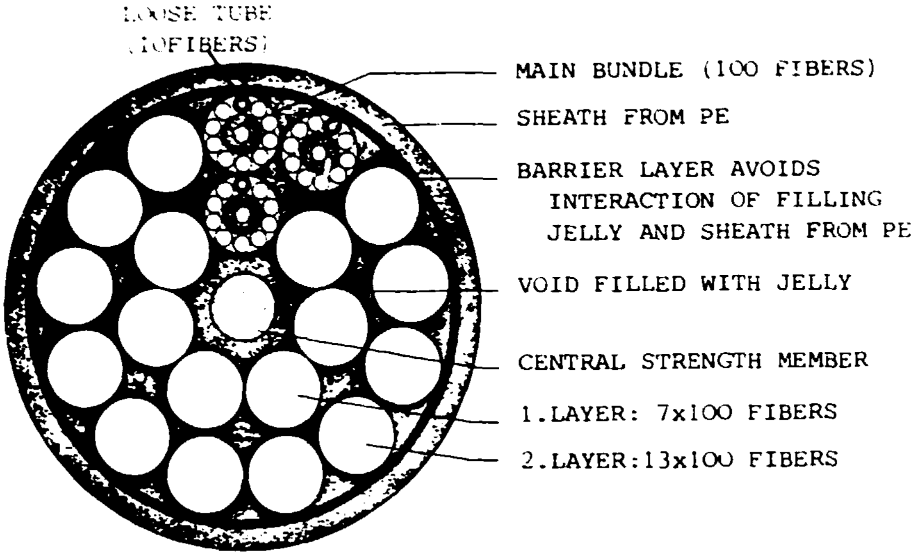

Fig.5.9: High-density bundle cable containing 2000 fibers. 20 main bundles similar to those depicted in Fig.5.1(b) are arranged around a central strength member /Mayr et al. 1983/, reproduced with permission.

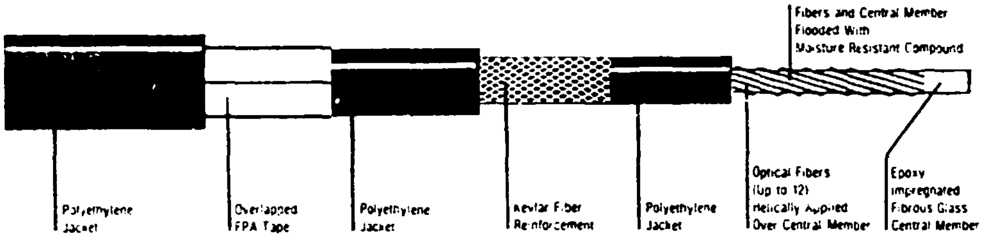

Fig.5.10: Typical cable configuration with fibers helically wound around a central strength member /Foot and Masterson 1980), reproduced with permission.

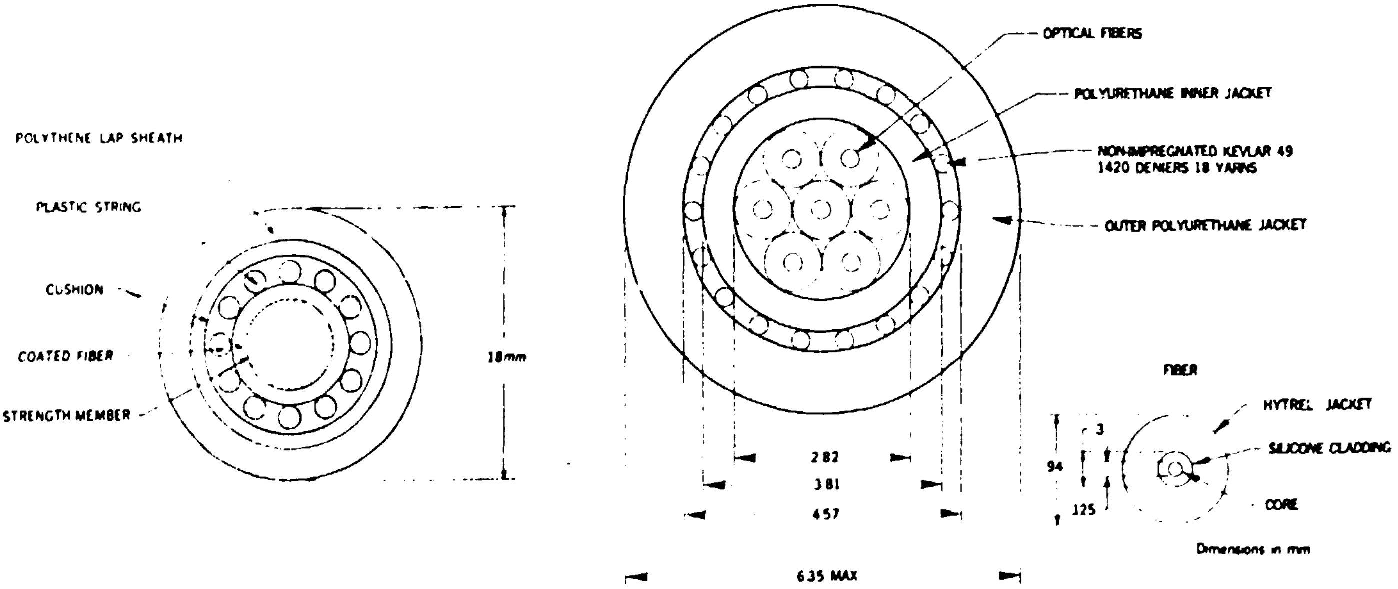

Fig.5.11: Generic fiber cable
(a) with fiber supported by soft cushions
(b) with fully supported fibers and outer strength members.

Reproduced with permission: Ch.K.Kao, Optical Fiber Systems: Technology, design and applications, McGraw Hill, 1982.

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. The resulting structure is shown in Fig.5.13. The advantage of this design is the high packaging density and the ease of connecting all 144 fibers simultaneously to another 144 ones with one connector. This structure is successfully fabricated by Western Electric for cabling multimode fibers.

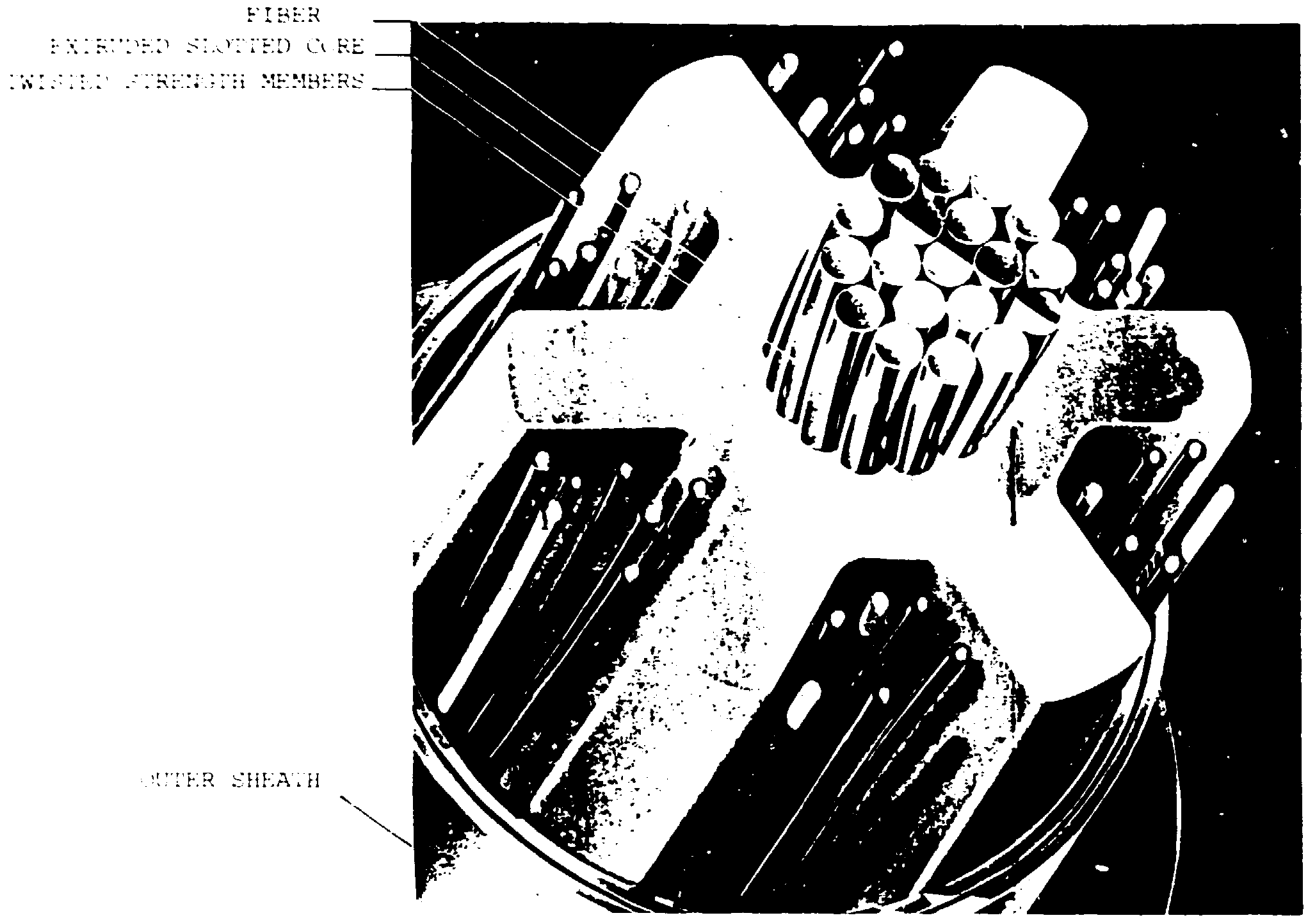

Fig.5.12: Perspective view of a slotted-core cable containing six fibers in each slot /Northern Telecom 1984/.

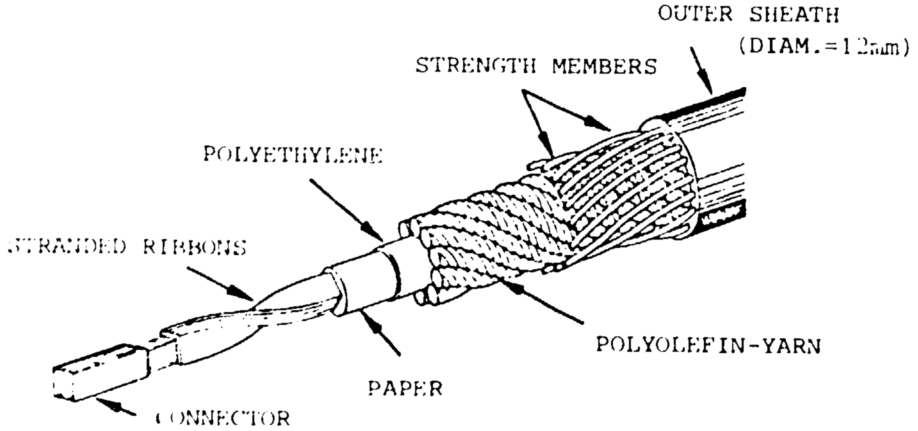

Fig.5.13: Stranded rectangular array ribbon cable /Rosenberger 1982/, reproduced with permission.

5.5 Cabling equipment

Jacketing machines for both loose-tube and tight jacketing are essentially extrusion machines. The fiber(s) is (are) fed through a cross-head which is supplied with soft plastic (e.g. nylon at 192°C) by an extrusion screw conveyer. A light vacuum keeps the meniscus of the molten plastic sufficiently small. A vertical or horizontal length gives opportunity for the jacket to cool before the jacketed fiber(s) is wound on a spool. For loose tubing, the jacketing machine has to provide the jelly for filling also.

Though there are special cable stranding machines for fibers available, the techniques and equipment do not differ from ordinary machinery used in conventional cabling of metallic wires quite some time. Smaller cabling companies have successfully adapted conventional basket cabling machinery for the cabling of optical fibers. Special attention has to be paid to apply a uniform tension of the fibers to be stranded. Most of the larger cabling companies rely upon self-designed stranding machines and extrusion heads which they sometimes offer on the market. For instance, Siemens has developed a stranding machine, based on the "SZ-stranding principle" where the spools containing the fibers are not arranged in a rotating basket, but where the fibers are loosely laid on light-weight 1-m diameter aluminium plates. With this machine very uniform tension is applied to the fibers, and, in principle, a nearly continuous cabling process is possible. The big advantage is the reduction of rotating mass.

5.6 Splices and connectors

In the world of copper conductors, splicing can be as simple as twisting two wires together and soldering them. Splicing optical fibers, however, is a much more complicated task. Special training, practice, and equipment together with patience and good coordination are necessary before the technician can make acceptable splices. Proper splicing is difficult for two principle reasons: (1) the hairlike optical fibers are so fine they are hard to handle, and (2) the two fibers must be precisely aligned to keep losses to an acceptable level. Many different fiber-splicing techniques have arisen during the evolution of optical fiber technology. The most wide-spread used one is the fusion splice. Fusion splices are made by thermally bonding together prepared fiber ends, as pictured in Fig.5.14. In this method the fiber ends are first prealigned and butted together. This is done either in a grooved fiber holder or under a microscope with micromanipulators. The butt joint is then heated with an electric arc so that the fiber ends are momentarily melted and, hence, bonded together. This technique can produce very low splice losses (< 0.1 dB for identical fibers). However, care must be exercised in this technique, since surface damage due to handling, surface defect growth created during heating, and residual stresses induced near the joint as a result of changes in chemical composition arising from the material melting can produce a weak splice. Electric arc fusion splicing equipment is now available from several manufacturers. The units are portable and self-sustained which is important to make splices in the field.

A technique applied to splicing multiple fibers formed in a ribbon is the V-groove alignment technique shown in Fig.5.15. The prepared fiber ends are first butted together with an adhesive or are held in place by means of a cover

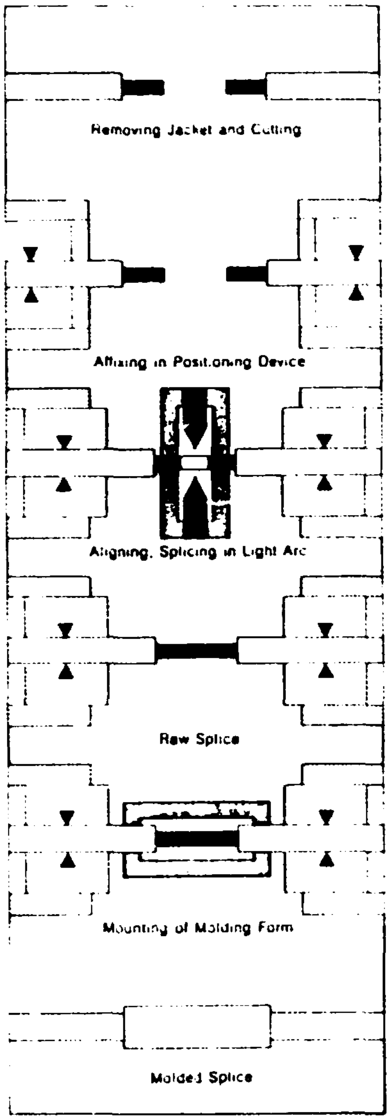

Fig.5.14: Steps in making a fusion splice. Telefunken electronic GmbH, Heilbronn, West Germany, reproduced with permission.

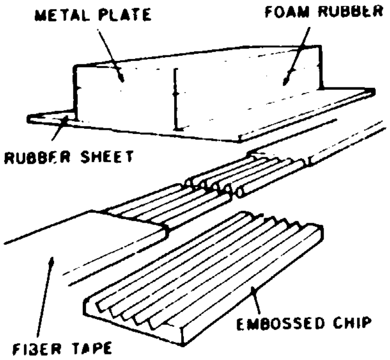

Fig.5.15: Ribbon cable splicing using the V-groove alignment technique /Gloge et al. 1979/, reproduced with permission.

plate. The V-shaped channel can be either a grooved silicon, plastic, ceramic, or metal substrate. The splice loss in this method depends strongly on the fiber size (outside dimensions and core diameter variations) and eccentricity (the position of the core relative to the center of the fiber).

Whereas splicing techniques are used to joint optical fibers/cables during installation or in the case of repair, there are some applications for removable connections. A wide variety of optical fiber connectors based on different principles of operation has evolved. Two types of connectors based on butt-end coupling and on ball-lens coupling, respectively, are shown in Fig.5.16.

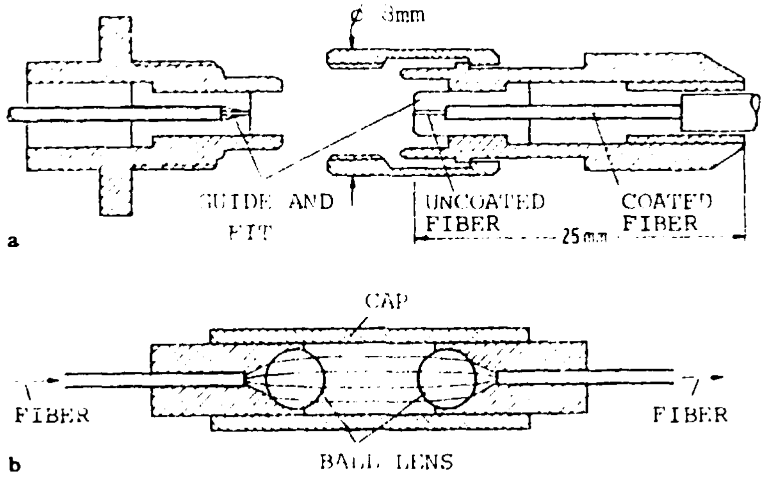

Fig.5.16: Optical fiber connectors based on the butt-end coupling scheme (a) and on the ball-lens coupling scheme (b) /Kersten 1983/, reproduced with permission.

6. 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. Also, there are still unresolved technical problems associated with transmission measurement methods, such as mode conditions of launched light with multimode fibers, temporal fluctuations of launching conditions in SM fibers, the condition of the fiber end, or the unpredictability of bandwidth of concatenated pieces of fiber. Still, some standard test methods for fibers have evolved and international standardization is impending, expecially for GI fibers /IEC 1982 - 46CO, 8, 9, 10, 11; EIA RS - 455/.

6.1 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. Also, non-destructive methods for routine characterization of preform parameters have not found widepread use. This raises a serious problem: Not before that almost all value has already been added to the fiber, it can be decided whether or not the product is useful. The requirements of buyers of optical fiber are demanding and the testing of more and more parameters is asked for. For the producer, every additional test reduces his yield due to inevitable rejections. There is not very much of a market for low quality fibers.

The reference /Marcuse 1981/ describes optical fiber measurements in detail, /Lovely 1984/ discusses still unsettled problems of defining fibers by a few quick measurements.

The fiber being drawn, the following parameters require testing:

- strength
- attenuation
- bandwidth (= baseband response)
- numerical aperture
- size
- concentricity
- cut-off wavelength (SM fibers only)
- polarization characteristics (SM fibers only)

6.1.1 Strength

Two categories of tests pertain to fiber strength. Both are performed in recognition of the fact that the strength of a given length of fiber depends on the depth of the deepest flaw in this length.

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. It has to be kept in mind that the coating of the fiber may assist in carrying the pulling load.

Second, tensile failure point of a selected number of fibers is determined as a measure of statistical quality control. The fiber under test is cut into pieces (0.5 - 50 m length) which are pulled in standardized apperatus until breakage /EIA RS-355-4 1981/ and the tensile strength of breaking force reported. As reported by e.g. /Blyler and DiMarcello1980/, the cumulative failure probability of the fiber pieces, plotted in a so-called Weibull-plot (Fig.6.1), gives important information on possible shortcomings in the drawing or coating process.

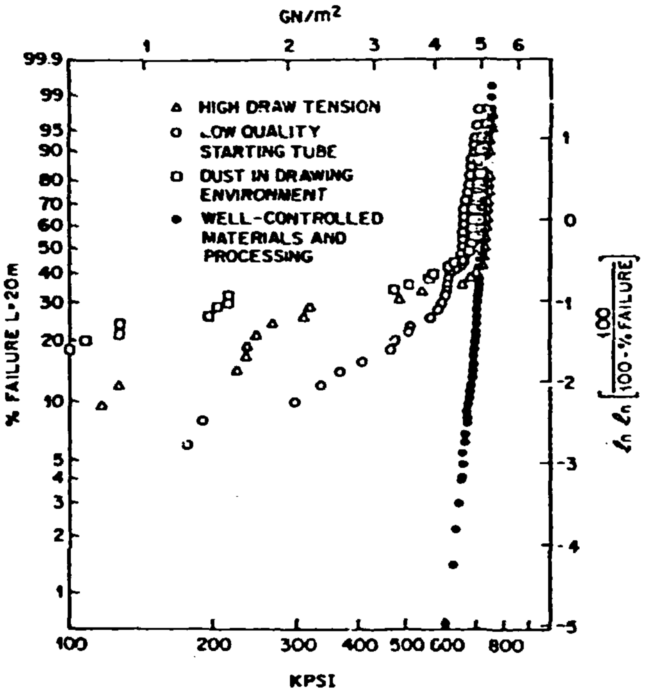

Fig. 6.1: Typical plot of percentage of failure of short lengths of fiber subjected to tensile strength test ("Weibull-plot") /Blyler and DiMarcello 1980/. Also shown is the influence of non-optimum production conditions (Note: this is a plot for high-strength fiber; actual production runs show lower overall strength). Reproduced with permission.

6.1.2 Attenuation

Optical attenuation is a parameter of interest for any fiber. It 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 definded. Standard "equilibrium mode launching conditions" /IEC 46C011 1982/ provide a power distribution of field patters at the fiber output which is substantially independent of the length of fiber. They are brought about by a special lens system or fiber launching systems (dummy fiber, mode scrambler).

Three reference methods are recommended by /IEC 46C011 1982/

- cut back
- insertion loss
- backscattering.

The schematic of the cut-back method is shown in Fig.6.2. The lamp as a light source may be replaced by a laser or an LED diode if only narrow wavelength loss is to be measured. The detector is a large area detector with spectral response compatible with the source. Chopping of the light serves to increase the signal-to-noise ratio of the measurement. First, the fiber is set in the measurement set-up and the output power recorded (P_1). Then, with launching conditions unchanged, the fiber is cut back at approximately 2 m for the launching point and the output power of this length (P_2) recorded. Attenuation is calculated from $a = 10 \log_{10} (P_1/P_2)$. The method has to be performed carefully for reproducible results.

In the insertion-loss method, the optical source and detector are connected via a short length of fiber for initial calibration (light power P_1). Then, the object under test is

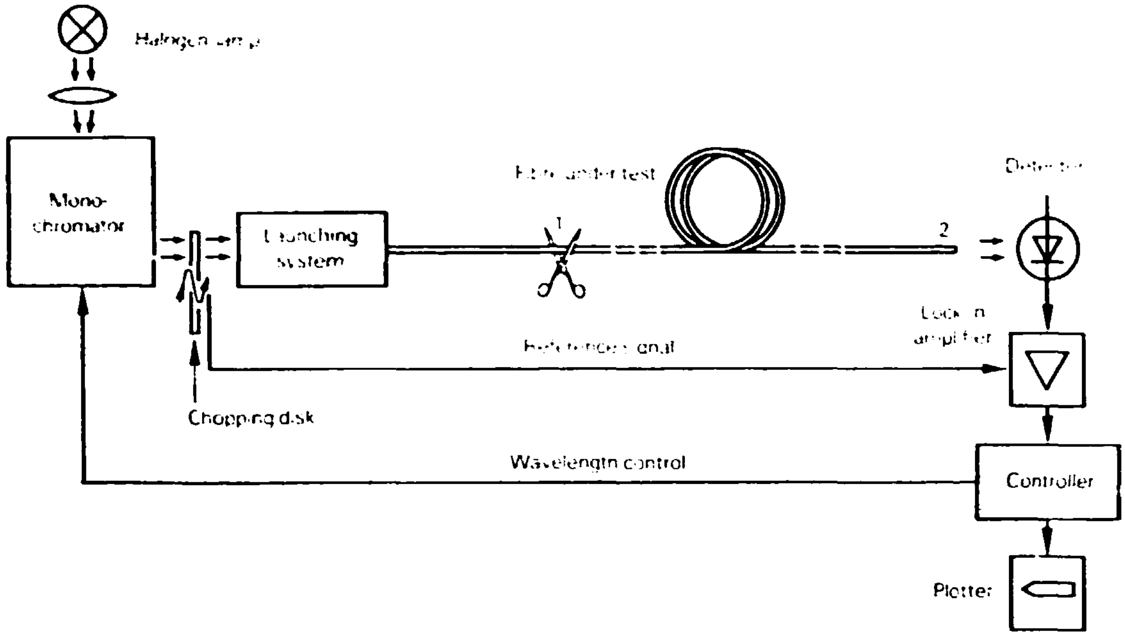

Fig. 6.2: Example of arrangement of test equipment used to make spectral attenuation measurement ("cut back method").

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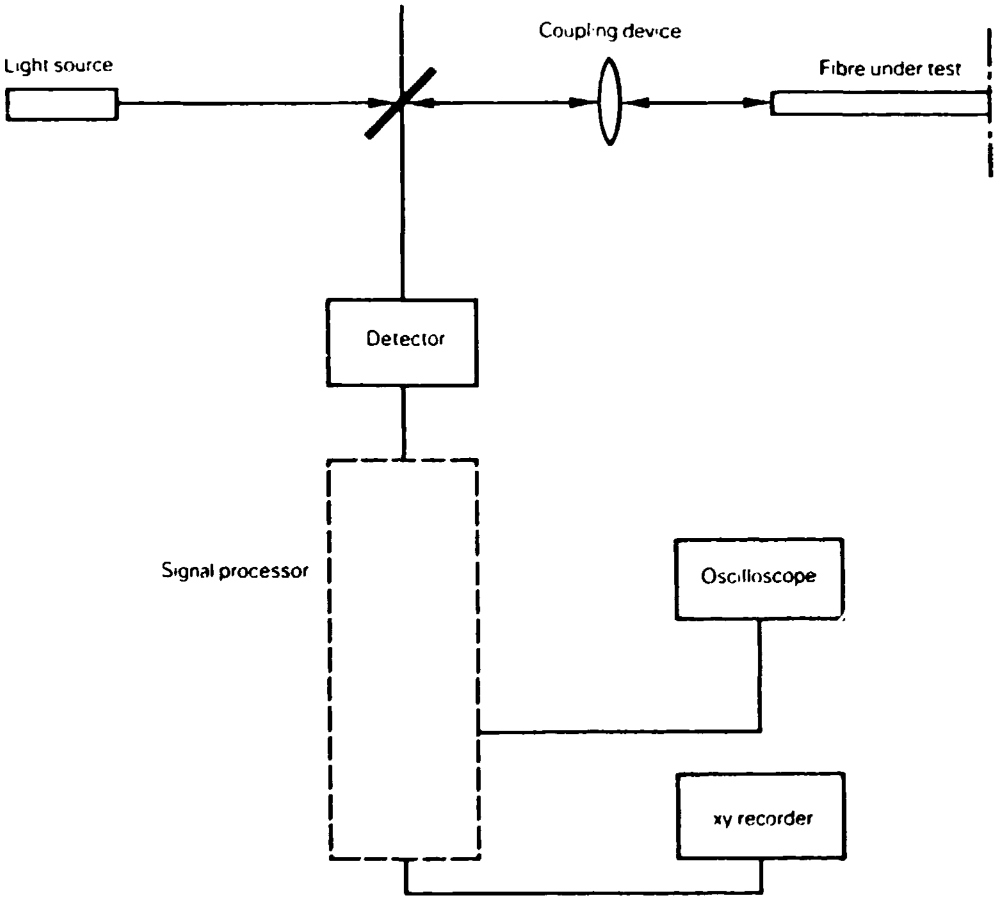

Fig. 6.3: Schematic of backscatter method (OTDR)

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inserted and light power P_2 recorded. Fiber attenuation is calculated as in the cut-back method, but it is necessary to correct for the connection losses. Sources and detectors are as specified above.

The backscattering method utilizes light pulses which are reflected by Rayleigh scattering in the fiber. The schematic is shown in Fig.6.3. Reflected light power and pulse transit time are plotted in a diagram which permits attenuation to be calculated between two locations on the fiber (Fig.6.4). Another name for this method is Optical Time Domain Reflectometry. OTDR apparatus is commercially available in self-contained form for 850 nm and 1300 nm. Due to low reflected signal levels and low dynamic range, it is customary to use a high power light source (laser) in connection with signal processing of the detected signal. Despite low dynamic range and other shortcomings, this method is popular because (i) the fiber has to be accessed from one end only; (ii) it also measures optical continuity (possible physical defects like bubbles or inclusions and their location); (iii) it gives a measure of fiber length when the group index of the fiber is known /IEC 46C09 1982/.

6.1.3 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.

Figure 6.5 shows a schematic of the frequency response test set-up. It is essential that the test wavelength is close to fiber's nominal operating wavelength. The optical wave is modulated by the swept baseband frequency. Under the

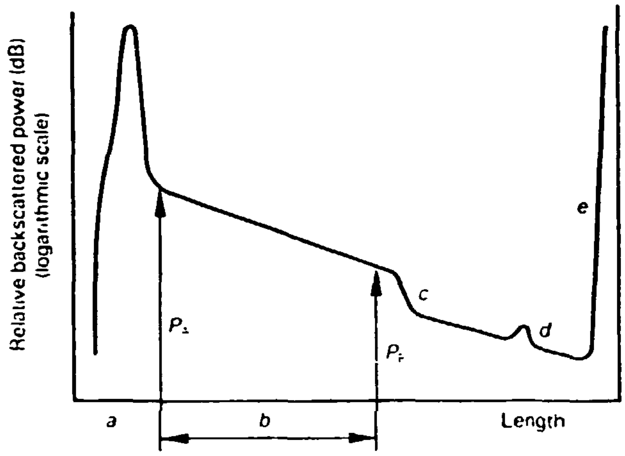

Fig. 6.4: Plot of typical OTDR test result /IEC 46(CO) 11 1982/. Attenuation can be calculated from $a = 5 \lg (P_A/P_B)$.

(a) reflections from coupling device, fiber input end and mode scrambler
(b) typical backscatter
(c) loss due to local defect or splice
(d) reflection due to dielectric defect
(e) reflection from fiber end

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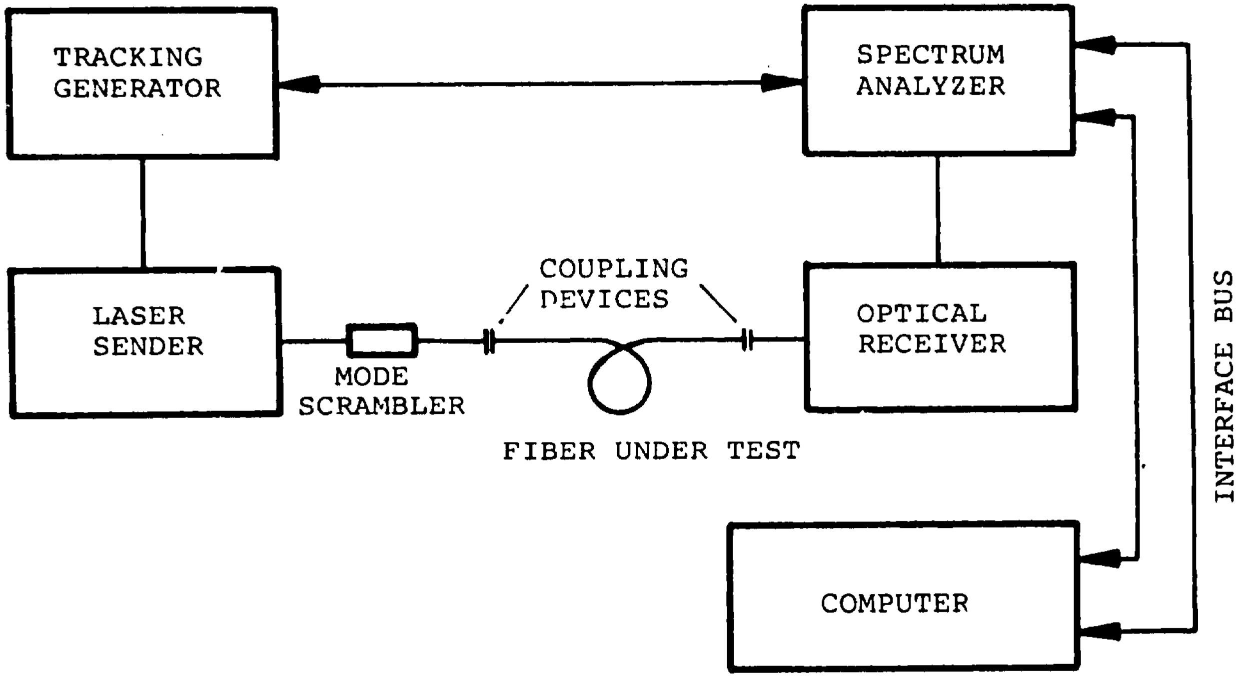

Fig. 6.5: Schematic of laboratory frequency response test set-up for measuring bandwidth.

assumption that the fiber's baseband response is that of a Gaussian low-pass filter, the frequency at which amplitude response is 6 dB (electrical) below its DC value is called "bandwidth". (Owing to the conversion mechanism from optical to electrical signals and vice versa, 6 dB in electrical signals correspond to 3 dB at optical signal level.) It is given for fiber lengths of 1 km.

The spectrum analyzer plus tracking generator (replaceable by a network analyzer) and the control computer are costly pieces of equipment but are commercially available. The wide-band electrical-to-optical and optical-to-electrical signal converters are even more specialized and are only beginning to become available outside the laboratory.

6.1.4 Additional tests - dimensions and numerical aperture

The IEC Document 46C08 lists a number of possible test methods together with the fiber characteristics covered (Table 6.1). It should be understood that this table encompasses all catagories of fibers, but not all tests are applicable to any one fiber category.

The most versatile test method is the near field light distribution (Fig.6.6, page 145). An incoherent white light source illuminates, via suitable input optics, one fiber end immersed in an index matching fluid. The output light from the other end is either viewed directly via a microscope or photographed or, more sophisticatedly, analyzed by a video analyzer or a small-area scanning detector. The latter case operates customarily with magnifying output optics (as shown in Fig.6.6). The refractive index profile can be determined and hence core dimensions.

Not for exact determination of dimensions, but as a test of compliance with dimensional specifications, the four-concentric-circle method is useful for outgoing inspection.

Table 6.1: Miscellaneous test methods for dimensions and numerical aperture /IEC 46E (CO) 8/.

Test method	Test	Characteristics coverd by test method
IEC XXC-6 IEC XXC-7 IEC XXC-8 IEC XXA-5	- Refracted ray - Near field light distribution - Reflected ray - Light interference	- Refractive index profile - Max. theoretical numerical aperture
IEC XXC-12	- Far field light distribution	- Effective core size - Effective numerical aperture - Light acceptance angle
IEC XXC-7	- Near field light distribution	- Effective core size
IEC XXA-1	- Refractive index profile	- Diameter of core - Diameter of cladding - Non circularities - Concentricity errors
IEC XXA-2	- Near field light distribution (imaging)	- Diameter of core - Diameter of cladding - Diameter of primary coating - Diameter of buffer - Non circularities - Concentricity errors
IEC XXA-3	- Four concentric circles	- Diameter of core - Diameter of cladding - Non circularities - Concentricity errors
IEC XXA-4	- Mechanical	- Diameter of primary coating - Diameter of buffer - Non circularities - Concentricity errors

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Apparatus is just as described; only a mask with four concentric circles, demarcating the lower and upper tolerances of core and cladding respectively, is inserted in the optical measuring system (Fig.6.7).

For the effective numerical aperture determination the far field light distribution has to be recorded (Fig.6.8, page 145). The detector accepts light only from a small solid angle. For the measurement procedure, it is moved along a spherical surface centered around the fiber end. When the fiber input end is fully illuminated, extrapolation of the optical field distribution yields a precise measure of NA.

6.1.5 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 /CCITT 1981/. The measurement is performed, in principle, as the described near field distribution method. Alternative, more simple methods include the "transverse off-set" method /Streckert 1980/ by which two SM fiber ends are moved across one another. Increments are in 0.1 μm steps and the transmitted light is recorded as a function of relative position.

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 measured /Deserno and Schicketanz 1983/. Alternate methods include comparison of normalized spectral attenuation of SM and multimode fibers /Corning 110 1984/.

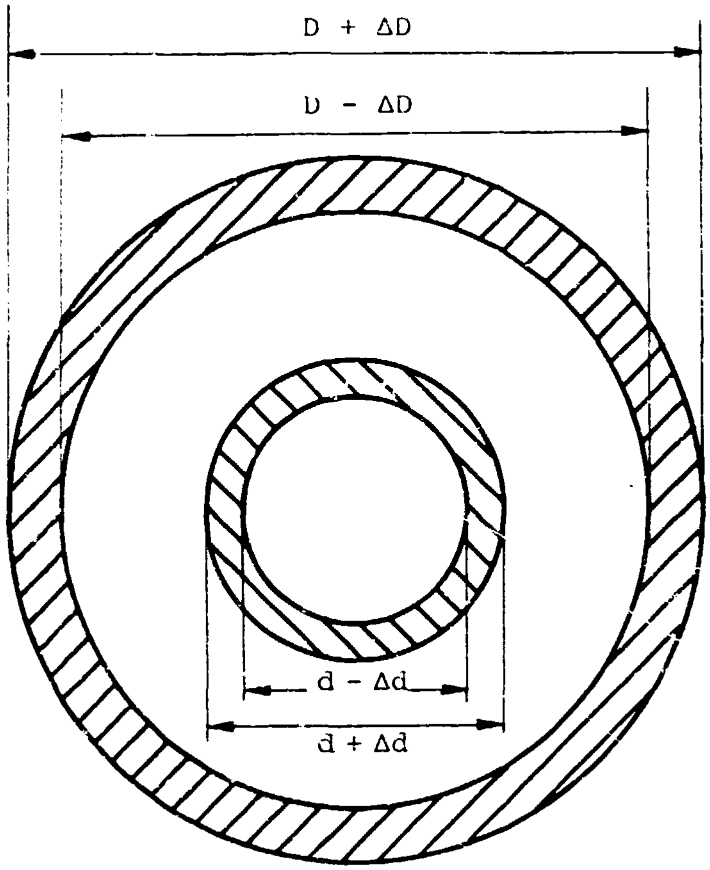

Fig. 6.7: Four-concentric-circle mask to check compliance of fiber cross section with specification (D... nominal cladding diameter, d... nominal core diameter; ΔD, Δd.. cladding/core tolerance) Acceptable tolerance area is shaded.

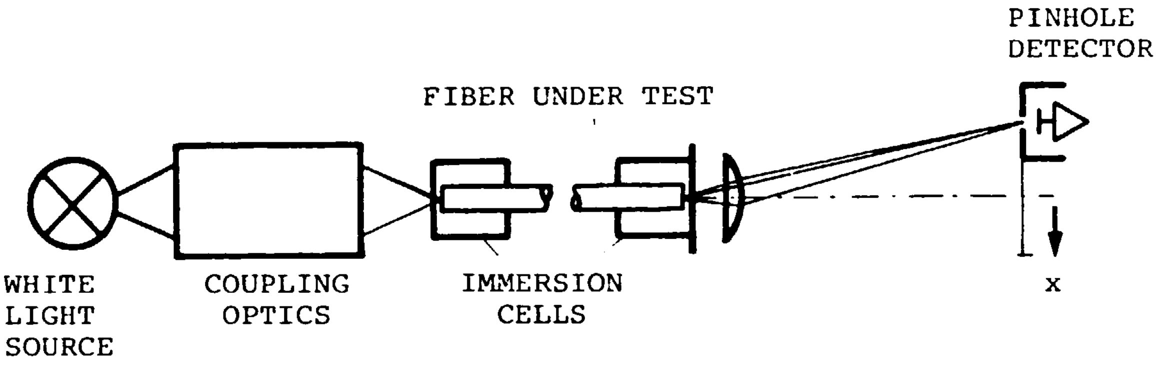

Fig. 6.6: Schematic of near-field method.

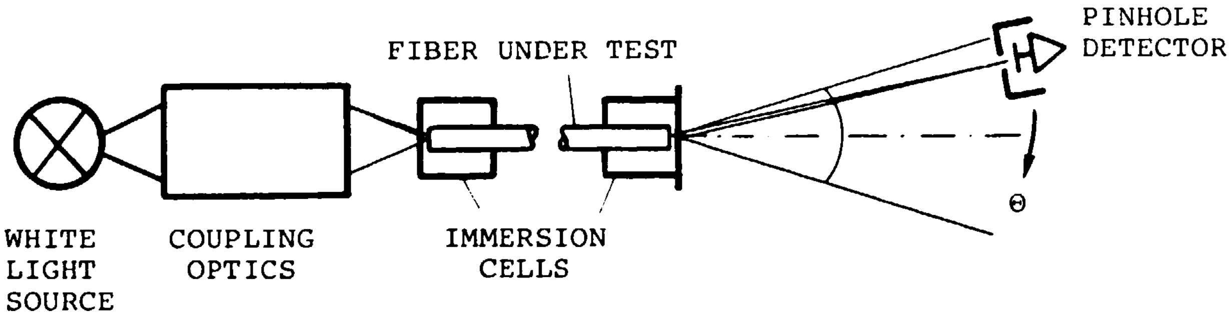

Fig. 6.8: Schematic of far-field method.

Mode field diameter and cut-off wavelength combined define an "equivalent step index" (ESI), by simple computation /Matsumura et al. 1980/. The ESI concept makes the transmission properties of SM fibers predictable, independent of the knowledge of the actual index profile.

In measuring SM fibers, the polarization of the light has to be heeded. The fiber itself has polarization properties: the beat length between orthogonal, nearly degenerate modes (which a "single" mode fiber does support) can be measured in an attenuation set-up with polarizer and analyzer.

Bandwidth is characterized by dispersion measurements, involving picosecond laser techniques. For instance, the time delay of a light pulse sent through the fiber for many different wavelengths may be used /Corning 111 1984/. Not every piece of fiber is tested, but statistical performance predictions based on actual measurement are customary. Bending of the fiber - which leads to selected radiation - identifies higher order modes present when used concurrently with the impulse response bandwidth determination. It is important for quality control of SM fiber production. Some small manufacturers do without bandwidth measurement of their SM fibers, however.

Altogether is the test instrumentation for SM fibers, in connection with their superior bandwidth and attenuation performance, more sophisticated than that for multimode fibers /Deserno and Schicketanz 1983/. The test methods for attenuation can be likewise applied to both types of fibers, with more technical effort on the detector side for SM fibers. No universal test methods have been established for SM fibers so far and testing of SM fibers requires very well equipped optical and electronic laboratories. Fiber manufacturers that have invested heavily in man-power for devising test methods and apparatus are prepared to sell or license their know-how in the field of testing and measurement.

6.1.6 Test organization

Two different methods prevail which are alternatively applied.

First, one test platform is equipped with the measurement instruments needed to fully characterize a fiber. One person at this platform performs several tests consecutively.

Second, a line of test platforms is set-up, one station containing instruments for a single test only. The fiber spool is handed down the line after each test has been taken. If automated, the second approach requires less skilled workers but their work is duller than in the first approach.

6.2 Quality control (QC)

The importance of QC is evident. It should be repeated and stressed at this point that there exists virtually no market for low-quality fibers. One large company even throws away fibers out of specification after a while, if it becomes evident that no customer for this fiber can be found.

QC measures are to be taken

- before,
- during, and
- at the end

of the production process.

As has been mentioned previously, 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. As a first step towards QC, areas for these production steps should be designed and built with clean-room facilities (doors, windows, air condition,...), say Class 10,000. Within these general areas, special work places can then be raised to Class 100 by special clean-room booths if so desired.

Next, incoming raw materials are inspected. It has turned out sufficient to check (or have checked by an independent laboratory) the purity of delivered high-purity chemicals in rather long intervals: First, whenever material of a new supplier is used, further, if an explicable problems with the fiber quality arise. A periodic check would be advisable but is not carried out in all fiber-producing companies.

For processes requiring substrate tubes, a very important measure of initial QC is the check of the tubes for uniformity of wall thickness and other parameters as described in Section 4.3.1.

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 (MCVD is best modelled at present), these recipes are still found largely by trial and error. Interesting enough, variations from nominally identical production units may exist; even the output from one lathe can vary in quality. Nevertheless, computer control is an important QC tool.

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. Whenever quality problems arise, they should be able to locate and eliminate the reasons of shortcoming. R & D people usually develop the above-mentioned recipes.

The preforms for GI fibers may be inspected for proper index profile by the method of /Presby and Marcuse 1979/ (Fig.6.9). As a QC measure this can eliminate faulty preforms before they are subjected to the drawing process. Preform testing is not generally done, however.

The most important step in QC is the final fiber testing, as described in Section 6.1. 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.

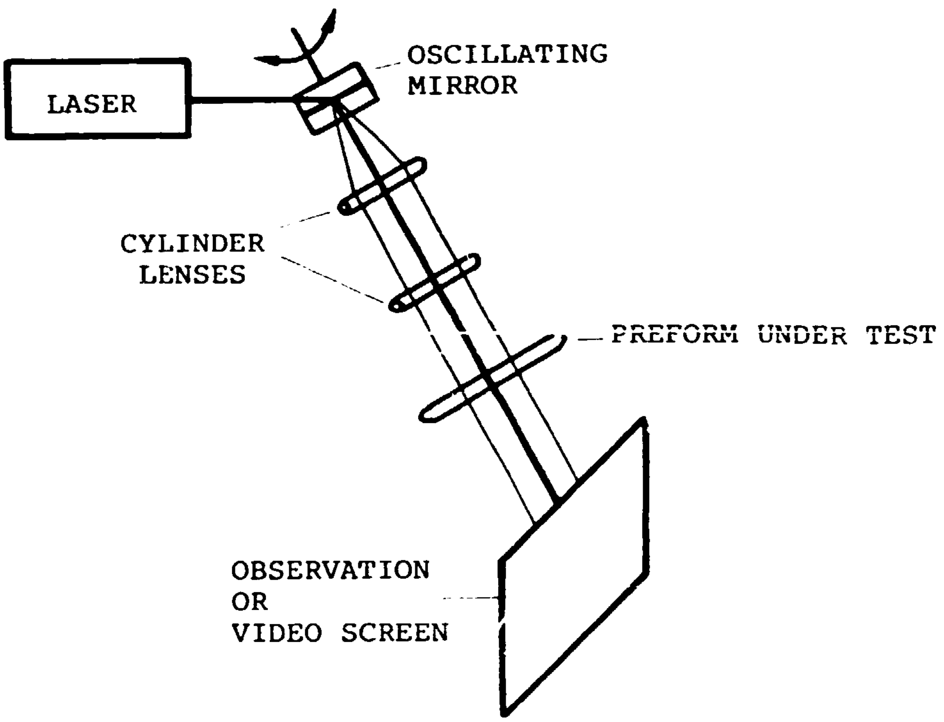

Fig.6.9: Arrangement for GI fiber preform testing.

6.3 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. To standardize the test subjects and the test procedures the IEC has worked out a draft listing up recommended tests:(IEC 46E, CO 12, 13; 1982), which is presented in Tables 6.1 and 6.2:

Table 6.1: 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 6.2: 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

Some of these tests are still under consideration and not yet fully specified. For the more important test subjects we will explain in more detail either the specified test procedures or procedures already commonly used.

- Mechanical evaluation

  - Tensile-strength test: The cable under test is wound in several layers around two drums as shown in Fig.6.10. The cable is strained to a specified value and the additional loss of 8 fibers is measured simultaneously. With such a configuration a cable length of 132 m can be tested /Sutor 1983/. A short light pulse is injected

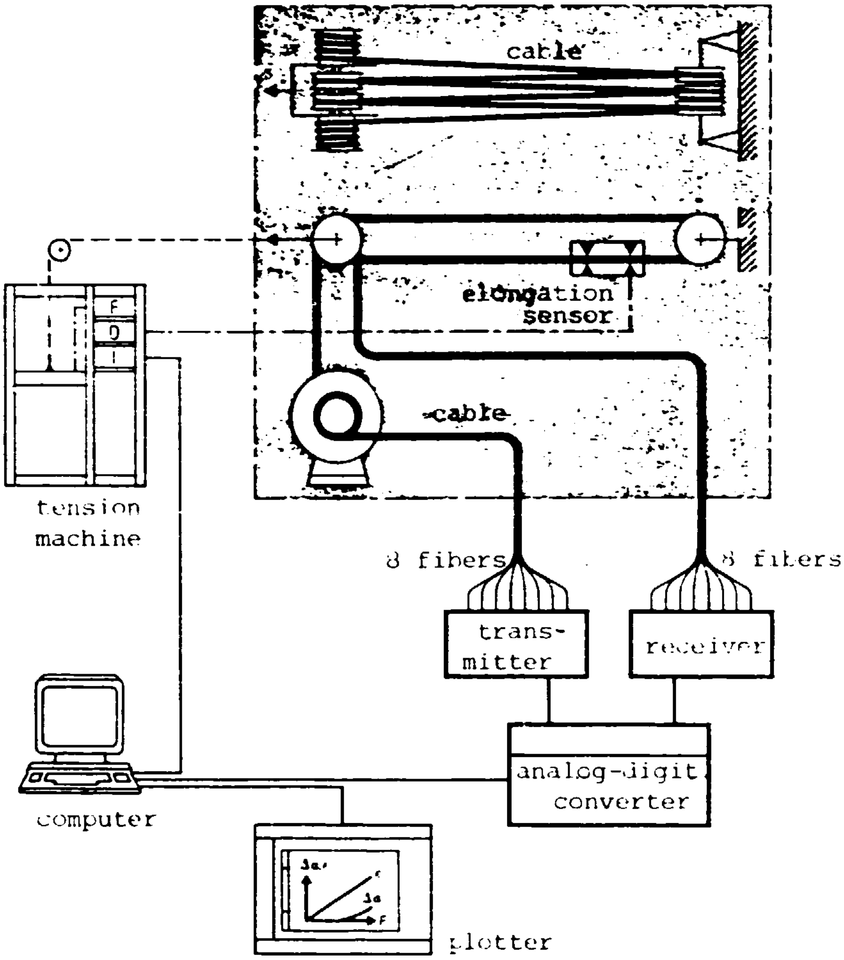

Fig.6.10: Computer-controlled tensile-strength test for optical cables.
$\Delta\alpha_\varepsilon$ is the loss increase, ε the cable elongation, and F ist the tensile force.
/Sutor 1983/, reproduced with permission.

into one fiber, and the delay time is compared with that of the unstressed cable. So the fiber elongation can be evaluated as a function of the cable tension yielding a diagram like that of Fig.6.11, where fiber strain and additional loss is monitored as a function of cable strain or tensile force, respectively.

- Bend test: The cable is fixed between two clamps with a specified radius and is bent alternatingly by an angle of ±90 degree (see Fig.6.12). The test parameters are bending radius and tension weight depending on the cable diameter. The number of bending cycles until breakage is recorded.

- Crush resistance: To test the resistance of the cable against a punctual radial force the cable is pressed between two flat plano-parallel metal plates whereas the additional loss is measured. The crush resistance depends primarily on the construction of the sheath, the fiber jacketing and the filling jelly.

- Twist test: Samples of the cable to be tested are subjected to twist cycles of 360 degree over 10 cm gauge length, until the cable breaks.

- Impact resistance: This test is performed by dropping a 1-cm radius spherical impact tool (hammer) onto the cable. The impact energy can be varied by the weight of the hammer and the dropping height. The test criterion is the number of impacts until fiber breakage (not sheath damage).

- Hydrostatic pressure resistance: Special cables like submarine cables are tested in high-pressure chambers to evaluate the loss performance under high hydrostatic pressure.

- Vibration test: To find out the influence of winds, aerial cables are exposed to vibrations, and the loss increase due to this stress is measured.

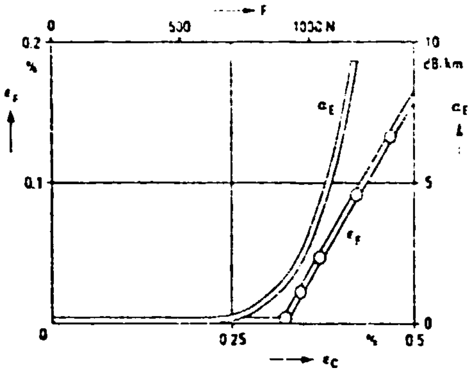

Fig.6.11: Fiber elongation ε_F and loss increase $\Delta\alpha_E$ as function of the cable tensile force F and the cable elongation ε_C typical for a 10-fiber loose-tube cable /Rosenberger 1982/, reproduced with permission.

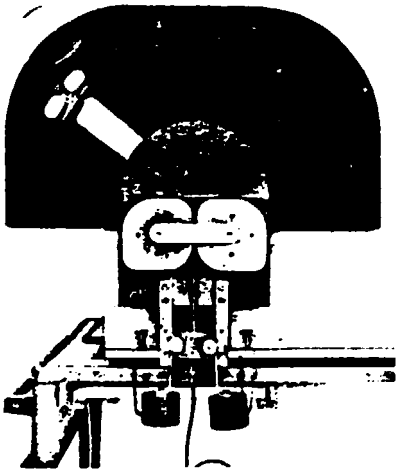

Fig.6.12: Bend test equipment: the fiber is bent ±90 degree around two clamps with specified radius /Sutor 1983/, reproduced with permission.

- Environmental evaluation
  - Temperature cycling test: Loss measurements are performed at the cable exposed to temperature (-55°C to +85°C) and humidity cycles in a climate chamber. These measurements are aimed at revealing the limits where the specifications are exceeded.
  - Moisture resistance: The loss increase after moisture cycling, immersing in 98% humidity at 50°C, is measured.
  - Fungus testing: Fungus test in accordance with Procedure 1, Method 508 of MIL-Std-810 3 is an example.
  - Resistance to axial water penetration: A piece of a jelly-filled cable is hung up with the upper open end exposed to water pressure. After a couple of hours the lower end is checked for water traces.

Cable testing is aimed at demonstrating the following:

1. Attenuation and dispersion: The cabling process has a negligible or controllable adverse effect on fiber attenuation and dispersion over the temperature range.
2. Tensile test: The cable has safely withstood tensile loading of the designed value.
3. Impact test: The cable has safely withstood designed impact loading at a single point on the cable.
4. Environmental tests: The cable has performed in a satisfactory manner at high and low temperature extremes and under conditions of vibration and moisture.

7. 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. First, basic prerequisites for fiber production will be discussed, then a detailed account of raw materials, semiproducts, energy consumption, labor force, storage requirements, waste disposal, transportation facilities will be given with reference to a (fictitious) standard production facility.

7.1 Requirements for fiber production

7.1.1 Basic requirements

Fiber production shares a specific basic requirement with modern semiconductor industry, i.e. ample supply of highly pure gases and other chemicals. To a lesser degree than in the semiconductor industry, familiarity with clean-room conditions is necessary. Chemical engineers are knowledgeable about setting up and supervising fiber production, as examplified by the term "chemical vapor deposition". For the design of fibers and their testing, communication and optical engineers are the proper specialists. General knowledge in the fields of electronic control engineering, computer-assisted automation of fabrication processes, is also required if dependence an outward specialists should not become critical. Repair capability of electric/electronic machinery should also be available.

7.1.2 Reference production facility

It is generally agreed that a production unit with an annual capacity of at least 100,000 km fiber is presently the limit of production making full use of economy of scale. To become more specific in defining the production requirements, a reference production facility will now be described. The underlying assumptions for the data as summarized in Table 7.1 are:

- day-round three shift production
- seven days a week production
- no outage time of machinery
- factory in operation 350 days/year
- all preforms used for fiber production
- yield of fiber from preforms 100%
- no jacketing or cabling included

If any one of these assumptions is not fulfilled, the capacity of the production facility is reduced accordingly.

Whereas the reference process (MCVD) has some special requirements which might differ from other processes of preform production, these difference are minor in view of the required chemicals, energy, labor force, etc.

7.1.3 Machinery and installations

The essential pieces of machinery of a fiber production facility of the type described in the previous section are:

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

The installation of distribution systems for both pure gases and burner gases require careful design.

Exact mass flow control of the pure gases to the inside of the substrate tubes is crucial for the production process. The feed system must be gas-tight and non-contaminating and

Table 7.1: Reference fiber production facility

Capacity

Work shifts:	3/day	
Work days:	7/week 350/year	~1000 work shifts/year
Preforms fabricated:	1/shift and product unit	
Number of preform production units:	6	6000 preforms/year
Fiber drawing speed:	130/min	
Number of drawing towers required:	2	
Fiber drawn from one preform:	17 km	100,000 km fiber/year

Fiber

Type	graded index, silica
Dimensions	50 µm core/125 µm cladding
Numerical aperture	0.2

Process

Type	MCVD
Deposition rate SiO_2:	0.6 g/min
Major dopant	GeO_2
Deposition efficiency Si:	60 %
Deposition efficiency Ge:	20 %
Percentage of length of preform used for fiber drawing:	70 %
Core:	deposited
Cladding: (no overcladding)	substrate tube 25 mm OD, 19 mm ID, 1200 mm length

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. Each production unit (lathe) will have its individual pure gase feed system.

The burner gases are distributed from central storage tanks to each production unit. Because of the flammability of hydrogen and the combustion-supporting property of oxygen, automatic safeguards against leakage, flow interruption, breakage of pipes must be incorporated in the distribution system. The oxy-hydrogen burners surround the substrate tubes along approximately one-third of their perimeter. Six flames are usual.

The glassworking 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 oxy-hydrogen burners is mandatory.

Modern CVD lathes are covered by hoods with large vision ports. 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.

All CVD preform production processes require lathes, except VAD. There, a vertical turning axis equipment is used instead (see Section 4.3.4.). The price of one production unit for VAD, however, is identical to the price of other CVD production units.

All preform/fiber manufacturers visited in the course of this study prefered to develop and design their production units themselves. The designs are then handed over to established producers of machinery and process equipment, who put together the equipment from mainly purchased subunits. Some fiber manufactures even implement their equipment designs by comparable procedures in-house.

A storage chamber with clean-room atmosphere takes up the preforms prior to drawing.

Fiber drawing towers can be purchased "ready-to-use", but again in-house designs (or at least modifications) are standard. As described in Section 4.4 a glass-melting furnace, a precision feed system of the preform, a fiber thickness monitor, a coating die, a coating curing furnace, a mechanical fiber take-up system and a process computer constitute the drawing tower's main parts.

The testing of the drawn fibers involves sophisticated and expensive optical and electronic test equipment. The required apparatus is described in detail in Chapter 6.

The process computers for the control of gas feed system, the lathes, drawing towers and testing procedures make up for a considerable portion of the necessary equipment. Besides the central processing units, numerous sophisticated sensors (e.g. pyrometers for tube, preform temperature, lasers for thickness monitors,mass flow meters, ...) are essential for proper process control. The results of the final tests are entered into a central computer via work stations, one connected with every test platform.

Besides the machinery, several small but specialized pieces of equipment are required for fiber production. They include measuring equipment for tube straightness, wall thickness and uniformity; precision scales; cleaning vessels for the tubes, glass-blowing utensils for tube set-up.

7.1.4 Pure gases and chemicals

The requirements for pure gases and chemicals is the most stringent and the most critical for optical fiber production. For the preparation of one preform as described the following approximate amounts of gases and chemicals are required (Table 7.2).

Table 7.2

Chemical		Purity	Amount
Hydrogen	H_2 (1)	technical	6,000 l NTP (2)
Oxygen	O_2	technical	3,000 l NTP
Oxygen	O_2	99,999 %	2,250 l NTP
Silicon tetrachloride	$SiCl_4$	99,999 %	500 g
Germanium tetrachloride	$GeCl_4$	99,999 %	90 g
Argon	Ar	99,999 %	150 l NTP
Helium	He	99,999 %	150 l NTP
Acrylates (coating)		special purpose	2 l

1) May be replaced by methane (CH_4)

2) NTP: amount of gas at 20°C and atmospheric pressure

Minor amounts of ultra-pure dopants like $POCl_3$, fluorides, BCl_3, etc. will also be required. They will become necessary if different fibers are to be produced. For consolidation, ultra-pure Cl_2 or $SOCl_2$ will be necessary. Several pure chemicals for cleaning and degreasing of substrate tubes are required.

The purity of the critical constituents ($SiCl_4$, $BeCl_4$, O_2, He, Ar) should be as high as commercially available. This is sometimes higher than given in Table 7.2. 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. In outside processes (OVPO, VAD), the tolerance to contaminants like $SiHCl_3$ (in $SiCl_4$) is higher but the purity requirement for the essential gases is not generally relaxed.

7.1.5 Waste treatment and disposal

The exhaust from the preform production unit is toxic and contains large amounts of chlorine. A scrubbing system, filtering solid particle and neutralizing the acidity, is essential. Per preform fabricated, an estimated 200 g of solid waste has to be safely taken care of, leading to 200 kg solid toxic waste per year. Proposals have been made to recycle the germanium from the exhaust, but this process is not yet standard /Bohrer et al. 1983/.

In the scrubbing system, a lye neutralizes the acidity of the exhaust from the lathe. Any purity/composition will suffice.

The cleaning liquids can be returned to supplier for re-use after purification.

Exhaust from the burner gases is non-toxic and uncritical; it can be released into the atmosphere.

7.1.6 Water supply

Cooling water is required in the deposition/consolidation step. It should be free from solid particles and reasonably pure so that it neither attacks the glass tube nor the plumbing pipes. Only tens of liters per minute are required.

7.1.7 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. Newly opened factories evidently have more stringent cleanliness rules in force. Rooms containing the preform production units are more tolerant to dust and moisture than the fiber drawing rooms. It is advisable to separate these rooms, as well as those for optical/electrical testing.

Preform production can be performed in rooms of Class 10,000 or worse. The glass-working lathes are contained in air-tight boxes, anyway.

Fiber drawing rooms should be of Class 1,000 to 10,000. In the case of the pristine glass fiber being protected by a tubular sleeve, the latter value will be amply sufficient. Within this sleeve, Class 100 clean-room conditions should prevail for best results in fiber strength and yield.

The rooms for optical/electrical testing of the fibers should be climatized for the convenience of the people working there, as is true for the other two types of rooms described. Exessive moisture (≥60% relative humidity) would, of course, be undesirable for the fibers also, even if it is already coated. Produced fiber should therefore be stored in a dry, dust-free environment.

Summing up, an air-condition system with control of temperature, humidity and dust particles is required for the factory.

7.1.8 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. Based on the data of Table 7.3 a nominal electrical power supply of approximately 1500 kW will suffice. Electricity will be consumed, a three-shift work day stipulated, more or less evently distributed over a 24 hour period.

Table 7.3: Electrical power consumption.

Preform production unit	5 kW	
6 production units		30 kW
Drawing tower	100 kW	
2 drawing towers		200 kW
Optical test station	2 kW	
6 test platforms		12 kW
Illumination		50 kW
Climatization/clean-rooms		1000 kW (peak)
Gas/water pumps		20 kW
Miscellaneous		200 kW
	Total	~1500 kW

7.1.9 Labor force

The requirements on labor force for optical fiber production, concerning as well number as qualification, are suprisingly low. This is true for actual, well-running production; in the initial starting-up phase highly qualified specialists are needed. Also, it should be noted that we have implicitely assumed that no R & D activities are going on in parallel to production. This question and its implications will be touched in more detail in Chapters 6 and 9 . In the following we shall consider two alternatives: a fully automated process under microprocessor control and a partly-automated process under manual control.

Fully-automated computer-controlled fabrication process:

A work shift would consist of a minimum of

2 semi-skilled workers operating 3 lathes each
1 semi-skilled worker operating 2 drawings towers
1 skilled workers for tube set-up, drawing procedure start up
1 technician as supervisor, trouble shooter (or skilled worker)
1 unskilled worker (transport,...)
1 semi-skilled worker for screening test

For a three-shift working day and one crew a reserve for personnel illness, leave, and other absence, this gives a subtotal of 28 persons on payroll.

For optical/electrical testing, the number of persons required is crucially depending on the quality already achieved in production of fibers. Typically,

10 people of semi-skilled status and
4 highly skilled technicians

will be able to do the job of testing the output of the production branch. (Currently, fiber producers employ optical and electronic engineers to design and devise efficient and valid test methods!)

14 persons

In addition, craftsmen like electricians, plumbers, glassblowers, further managers, accountants, typing clerks will be needed. At least one chemical, electronic (control), optical, and communications engineer each should also belong to the staff. Their task would be to garantuee essentially uninterrupted production of high-quality end products. The entire number of this "support" personnel is estimated to one half of the production people, i.e. at least 21 persons

Estimate of total employees 63 persons

Semi-automated production process:

This alternative would, in general, involve more people and such of higher qualification in exchange for less sophisticated and cheaper machinery. In regions, where technically well trained people are comparatively cheap to be hired and the creation of jobs has high priority this way of producing fibers could be considered. It must be kept in mind, though, that a possible saving in machine investment would only be marginal.

At the most, as many people as enumerated in the fully-automated scheme could be kept busy.

Training of workers is usually done on the job. Senior workers train their younger or new colleagues ("snow-ball system"). In USA and Japan, a majority of the semi-skilled workers are high school graduates.

The stated numbers of required personnel is for production only. In every company visited there are also people involved in at least process development if not basic research. These staff, highly qualified, are not included in the above counts.

7.1.10 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.

The ultrapure gases He, Ar, O_2 are kept in compressed state in pressurized cylinders at about 10^7Pa (100 bar). Oxygen supports immediate combustion of almost any substance and is particularly incompatibe with hydrocarbons. It should be therefore kept outside the factory in a safe place.

The gases feeding the burners for heating the silica tubes are hydrogen and oxygen. Hydrogen is highly flammable in air, in almost any mixing ratio. Storage outside to plant buildings is mandatory. The two burner gases can also be stored under pressure around 10^7 Pa, in suitable pressure vessels. A sophisticated feed system with leak detectors and emergency cut-off valves distribute the gases to the different burners and lathe and should safeguard against catastrophic damage in the case of equipment malfunction.

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. They must also be stored in dry and clean places.

To give a specific picture of the storage requirements assume that the material for one month's production of the referency production facility should be permanently available (Table 7.4). Minor amounts are not listed.

Table 7.4: Major storage requirement for the production or 8,500 fiber kilometers.

Item		Amount	Volume	Remarks
Silica tubes		500 pieces	$\geq 1\ m^3$	
Burner gases:	H_2	3×10^6 l NTP	$30\ m^3$ (at 10^7 Pa)	pressure vessel
	O_2	$1{,}5 \times 10^6$ l NTP	$15\ m^3$ (at 10^7 Pa)	pressure vessel
Pure gases:	O_2	$1{,}1 \times 10^6$ l NTP	$11\ m^3$ (at 10^7 Pa)	special cylinders
	Ar	$7{,}5 \times 10^4$ l NTP	negligible	
	He	$7{,}5 \times 10^4$ l NTP		
	$SiCl_4$	250 kg		
	$GeCl_4$	45 kg		
Spools with produced fiber		3,000	$300\ m^3$	average 3 km fiber/spool

7.1.11 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. For instance, the fiber output of a three-shift work day weighs less than 40 kg. Lightweight spools (styrofoam) help keeping the transported mass low.

The volume to be transported ($10\ m^3$ per day, see Table 7.4) has to be calculated with. On the input end of the factory, it should be kept in mind that vans with pressurized gas vessels are heavy and bulky. For them, access to the factory must be provided.

7.2 Requirements for plastic fiber production

The requirements for the production of plastic fibers overlap to a high degree with the requirements of the chemical industry for making polymers of styrene and methyl-methaacrylate. Reference /Bartholomé 1980/ gives tailed descriptions of machinery and raw material requirements. As mentioned earlier, fibers are drawn by a double crucible method from the vessels containing the polymer. The core polymer makes up for almost the complete fiber mass. Approximately 1 kg of polymer yields 1 km of plastic fiber with 1 mm diameter.

7.3 Requirements for optical cable production in a reference 5,000 km/year production facility

Machinery:

Central parts of the machinery are

- cable stranding machines
- fiber jacketing machines
- test equipment.

For this reference facility, production of a standardized 10-fiber optical cable is assumed. The size of the production capacity is chosen to absorb 50,000 km fiber/year, the estimated output of the adjacent fiber production unit (Section 7.1). This places the capacity around 5,000 km optical cable/year.

Quick calculations show that one stranding machine and two fiber jacketing devices, each running 2 shifts/day have enough capacity to perform the task. Additional machinery is needed for cable testing. This includes one bend test machine, one machine to test tensile strength, climate box, splicers. Optoelectronic test equipment will be supplied by the fiber production facility, if necessary. Some transportation devices are also needed.

Materials: The strandard optical cable is assumed to have the following specifications:

strength member	Kevlar 49, 2.1 mm diameter
fiber	10 (125/50) graded index fibers
jacketing	tight nylon jacket
sheath	paper
cable jacket	PVC or PE

The optical cable is filled with petrolate-jelly to inhibit water migration.

Table 7.4: Materials in 10-fiber standard optical fiber cable.

material	volume (cm^3/m cable)	g/cm^3
Kevlar 49	3.46	1.45
PVC or PE	33.0 33.0	1.34
Nylon	7.8	0.93
Petrolate jelly	5.00	1.40

These materials allow the production of a cable with ~7 mm diameter, ~65 kg/km weight, tensile strength 100 kp, operating temperature ≤50°C, which meets the requirements of many telecommunication applications.

Labor: Production requires 2 dayshifts, cable testing 1 dayshift. The manpower requirements of one dayshift are in detail:

- fiber jacketing	1 semiskilled per jacketing machine = 2 semiskilled	
- cable stranding	2 semiskilled	
- transportation	2 unskilled	
- supervision	1 skilled	
cable production/shift		7 workers
- cable testing	2 skilled 6 semiskilled	
- production scheduling, trouble shooting service & repair	1 skilled 1 highly skilled	
		10 workers

Making allowances for a 50% reserve personnel this gives a total of 30 jobs for 1 highly skilled, 6 skilled, 17 semiskilled, 6 unskilled worker.

Energy:

stranding machine	50 kW
jacketing machines 30 kW each	60 kW
climate box, testing machinery, illumination, transport, miscellaneous	800 kW
	~1000 kW

8. CAPITAL INVESTMENT

8.1 Introduction

The study group collected, during its travel activities, data on investment requirements, raw materials, fiber prices, and labor costs. The general task of this data collection activity was to derive estimates of investment requirements and cost factors for a fiber production facility with nominal capacity of 100,000 fiber kilometer per year. The results and implications of these investigations are presented below. In the following data with an asterisk indicate results of our investigations, unstarred data are estimates. All amounts are given in US dollars.

8.2 Capital investment for a 100,000 km/year fiber production facility

The visited production facilities were of different sizes, those of comparable capacity use a factory hall of approximately 4,000 m^2 size and 5 m maximum height. Additionally 500 m^2 space for storage of silica tubes, gases, other chemicals, deliverable fiber is needed (Table 7.4). The factory hall should be airconditioned.

Additionally, an administration building is needed. This building is shared with an optical cable production facility and supplies the following services:

- office space for executives and other administrative personnel
- rooms for production personnel (wardrobes, bathroom, recreation)
- computer center

Depending on the climate of the country all these rooms or only parts should be climatized.

Table 8.1: Investment in buildings.

factory hall	4000 m^2	280 $/$m^2$		1,120,000 US $
storage space	500 m^2	280 $/$m^2$		140,000 US $
administration bldg.	500 m^2	840 $/$m^2$	(50%)[1]	210,000 US $
furniture, equipment	(50%)[1]			55,000 US $
				1,525,000 US $

Chapter 7 described the necessary machinery for a 100,000 km/year fiber production plant. Calculations in Chapter 7 are based on technically minimal requirements. This means service times and machine outage times are excluded from consideration. To give a reasonable estimate for production and investment costs, these factors must be taken into account. It seems therefore reasonable to add two MCVD preform production units and one drawing tower as reserve capacity to the figures of Section 7.1.2.

The other factors of capital investment are: the electronically controlled gas supply system for the preform production units, electrical installations for preform production units, drawing towers, scrubbers, climatization, test stations, electronic equipment, tube testing equipment, air conditioning, clean rooms.

Clean room conditions with the following specifications are assumed. The factory is completely climatized to guarantee clean room conditions of class 10,000. Glass working lathes are contained in airtight boxes, the critical parts of the drawing towers are protected by tubular sleeves with class 100 clean room conditions inside.

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1) Shared with cable production facility

The computer control equipment is assumed to consist of two medium sized computers to guarantee availability of 99%, terminals, tape stations, disk drives, communication networks for computer controlled production.

Investment cost estimated for machinery and equipment are summarized in Table 8.2.

A short note concerning investment requirements of other processes seems necessary. With regards to all machinery and equipment except the preform production units, there is no significant difference. OVD or VAD processes require differently equipped glass working lathes, the Philips process uses a basically different energy supply system. Since there are no price data directly available for these preform production units, a precise calculation is not possible but it seems to be a sound assumption that prices will not differ significantly from the prices of Table 8.2. This is definitely true for VAD machines.

Table 8.2: Investment in machinery and equipment.

1)	Preform production:	
	8	MCVD glass working lathes 500,000 US $ each
	8	airtight boxes, 15,000 US $ each
		Gas distribution system
		Scrubbing tower
2)	Fiber drawing:	
	3	drawing towers (including furnace and computer control) 500,000 US $ each
	3	tubular sleeve, clean rooms 15,000 US $ each
3)	General:	
	Climatization, clean rooms	
	electrical installations	
	electronic equipment	
4)	Miscellaneous (12%)	
		Total

4,000,000 US $
120,000 US $
200,000 US $
280,000 US $

1,500,000 US $
45,000 US $

1,000,000 US $
80,000 US $
1,100,000 US $
1,000,000 US $

9,325,000 US $

8.3 Capital investment for an optical cable productio. facility

It is assumed that this cable production facility should produce optical cables, using up all the output of the optical fiber production facility. As shown in Chapter 9 this means that approximately 50,000 km fiber per year can be expected as available input. For this purpose the following machinery and buildings are required.

Assuming the production of the ten-fiber cable 5,000 km of cable must be produced annually. (Note that it is a simplification of real life assuming that only one type of cable is produced.) Stranding machines typically operate at a speed of 1 km cable/hour, so approximately 5,000 machine hours are required. This can be done with one stranding machine, running 2 dayshifts throughout the year (300 work days) and some 15 weekend shifts.

The second major part of required machinery are jacketing machines. A current value of the speed of fiber jacketing is 2 m/sec (= 7,200m/h). Jacketing of 50,000 km fiber/year takes therefore approximately 7,000 h, so that two jacketing machines seem appropriate.

For testing the following equipment must be provided:

- bend test machine
- tensile strength test machine
- climate box.

Since conventional stranding machines are long and bulky, the building must be approximately 70 m x 20 m.

To store the production of one month and raw materials including fiber, strength members etc. ample storage capacity is required. Climatization is not required, severe climate factors excepted.

These considerations, together with estimated and polled prices, lead to the capital investment estimates of Table 8.3, if this facility is to be newly built, and if the administration building is shared with the fiber production unit.

Some remarks are in order to interpret these figures correctly. The analysis assumes that the entire facility must be erected from nil. Since optical cable production basically requires the same machinery, with some minor adaptions, as conventional cabling, dramatic reductions in investment costs are possible, if an existing cable production plant is adapted for optical cable production. Estimates for these adjustment costs as given by firms visited, converge around 500,000 US $. It should be noted, though, that completely new erection offers the option to buy most modern cabling equipment, tailored specifically to the needs of optical cables.

Table 8.3: Capital investment for a 5.000 km/y fiberoptic cable production facility.

1) Buildings:		
factory hall 70 m x 20 m x 5 m, 280 US $/$m^2$	392,000 US $	
storage space 200 m^2, 280 US $/$m^2$	56,000 US $	
administration building, furniture equipment (50%)	266,000 US $	
	714,000 US $	714,000 US $
2) Machinery & equipment:		
1 stranding machine	390,000 US $	
2 fiber jacketing machines 28,000 US $ each	56,000 US $	
1 bend test machine	28,000 US $	
1 tensile strength test machine	110,000 US $	
2 splicers 30,000 US $ each	60,000 US $	
1 climate box	167,000 US $	
	811,000 US $	
Miscellaneous (10%)	80,000 US $	
total machinery & equipment	891,000 US $	891,000 US $
Total investment (building plus machinery & equipment)		1,605,000 US $

9. ECONOMICS OF PRODUCTION

9.1 Fiber production

This chapter presents a detailed cost calculation for fiber production in a nominal 100,000 km/year production facility using the MCVD process for preform production. The following assumptions underly the analysis:

- production of a graded index fiber (50 μ/125 μ core/cladding diameter)
- prices for silica tubes, gases, pure gases and other chemicals are taken from current observations in industrialized countries
- wage level and structure of wages are as follows:
  a) production: four qualifications of workers are distinguished: unskilled (μ = .6)
  semiskilled (μ = .8)
  skilled (μ = 1.0)
  engineer/technician (μ = 1.5)

  The factor μ describes the wages of the respective group of workers relative to the wage of a "skilled" worker. These ratios are taken from experiences in developed countries.

  b) administrative overhead:
  In addition to the four groups already characterized there is the group of managers and their assistants. These persons are assumed to earn the following annual salaries.

1) president	80,000 US $
2) heads of departments	40,000 US $
3) assistants of managers	μ = 1.8

  The administrative personel is shared with an adjacent optical cable production facility. Assistants of managers are assumed to be highly qualified technicians, optical or electronic engineers, chemical engineers.

c) weekend shifts, nights shifts:
Wages in weekend shifts are 2.5 times the wages of regular day shift wages, the corresponding factor for night shifts is 2.0.

d) For the hourly pre-tax day shift a wage rate of 10 US $ is assumed for skilled workers.

e) A factor of 1.5 is introduced for the relation of actual labor costs to wages paid to workers, to allow for social security contributions of the employer and other wage by-costs.

- machine outages are assumed not to consume more than 10% of the total production capacity in each production step
- the yield of preform production is 70%
- the yield of fiber drawing is 90%

Actual fiber output will therefore be 50,000 km of salable fiber per year. Other assumptions are introduced when necessary. Expenses and revenue are calculated using these assumption. The effects of any change of assumptions can easily be tracked and calculated using the scheme developed in this chapter.

9.1.1 Profit and loss statement of a 100,000 km/year fiber production facility

Starting from Table 9.1. Profit/Loss statement, the following sections give a detailed account of revenue and cost factors for different steps of productions and of expenses for overhead, depreciation, service costs etc.

Table 9.1: Annual Profit/Loss Statement of a 100,000 km/year fiber production firm (all figures in US $).

Net Sales		15,000,000
Cost of Sales		6,190,000
Preform production	3,376,000	
material	1,971,000	
energy	22,000	
labor	1,383,000	
Fiber drawing	994,000	
material	695,000	
energy	98,000	
labor	201,000	
Quality testing	507,000	
energy	3,000	
labor	504,000	
Royalties (5% of net sales)	750,000	
Miscellaneous	563,000	
Gross margin on sales		8,810,000
Expenses		2,098,000
Depreciation	1,003,000	
buildings	71,000	
machinery	932,000	
Climatization, clean rooms	163,000	
Service costs (machinery)	467,000	
Overhead personnel (50%)	465,000	
Earnings from operation		6,712,000

9.1.2 Net sales

The revenue and cost calculations are based on the specifications of Chapter 7.1.2, Table 7.1. Starting with 6,000 preforms/year and 10% production outages one arrives at 5,400 preforms/year. Only 90% of the preforms are assumed to be further processable, be it because of the length taper (Section 4.3.1), be it because of breakage or non-conformity to quality standards. Lossed due to drawing machine outages (-10%) and low-grade quality (-30%) during fiber drawing reduces this figure to ~ 50,000 km/year of salable high quality fiber.

To calculate net sales the current world market price of 0.3 US $/m is taken.

The overall yield of approximately 50% is very sensitive to production conditions. If one succeeds to lower the losses due to inferior fiber quality by 10 percentage points another 8,000 km fiber could be sold, which would raise net sales by 2,400,000 US $.

9.1.3 Cost of sales

Cost of sales consist of the costs of those inputs that vary with the scale of production (variable costs): material inputs, labor, energy, royalties etc. In fiber production cost of sales can be imputed to five different sources:

- preform production
- fiber drawing
- quality testing
- royalties
- miscellaneous

Preform production. According to Table 7.2 the cost of chemicals for preform production are calculated as follows (Table 9.2).

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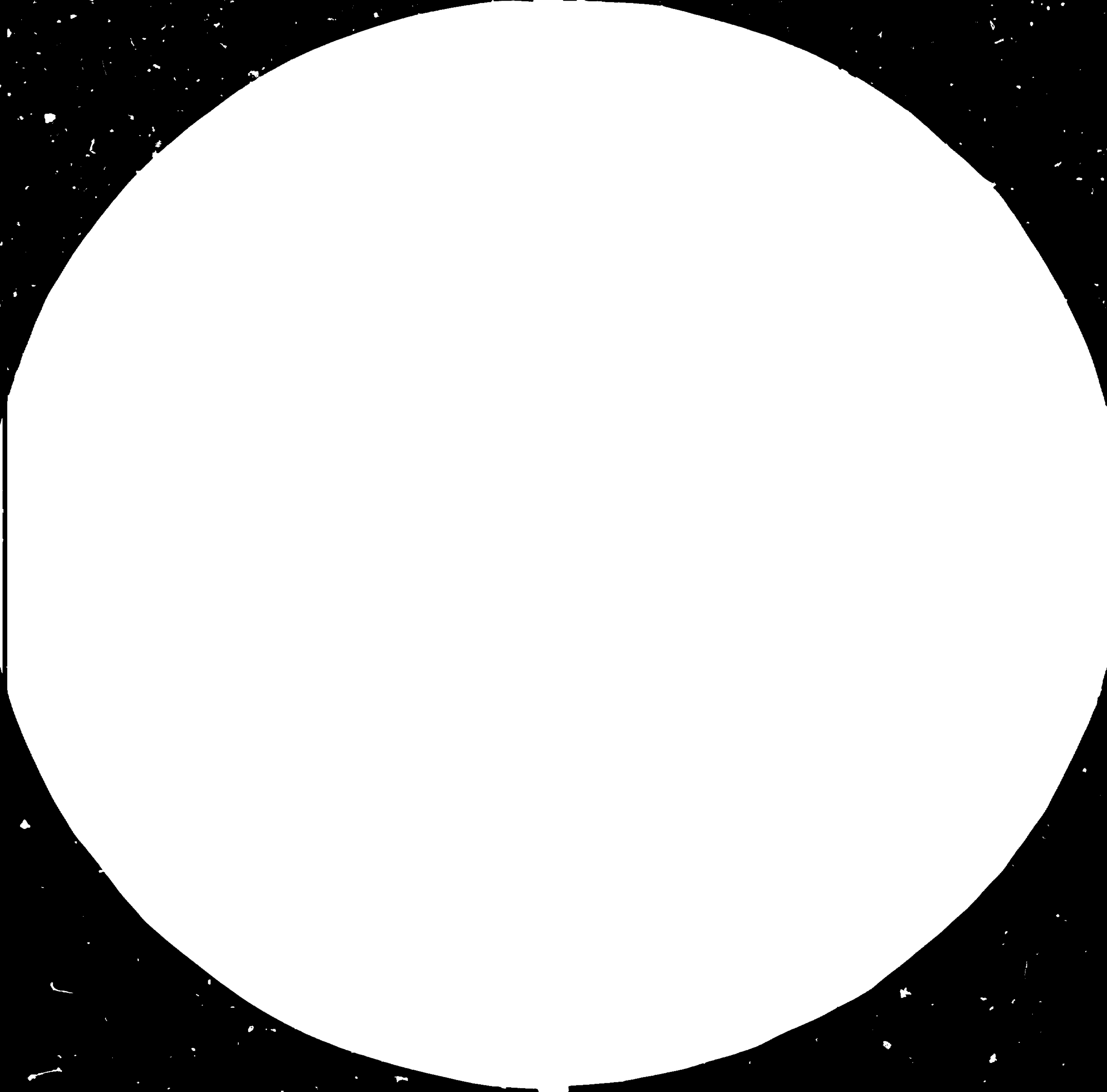

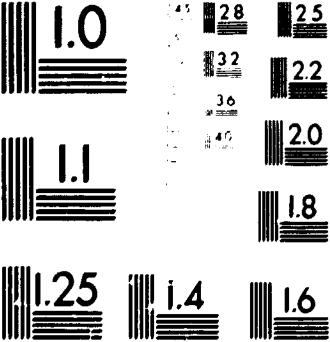

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Table 9.2: Cost calculation for <u>one</u> preform (graded index fiber).

Chemical	Purity	Amount	Price	Cost (US \$/Preform)
H_2	techn.	6,000 l	12.67 \$ / 10,000 l*	7.60 \$
O_2	techn.	7,000 l	7.78 \$ / 10,000 l*	5.45 \$
O_2	99.999%	2,250 l	322.22 \$ / 10,000 l*	72.50 \$
$SiCl_4$	99.999%	500 g	9.00 \$ / kg*	4.50 \$
$GeCl_4$	99.999%	90 g	800.00 \$ / kg* *	72.00 \$
Ar	99.999%	150 l	72.22 \$ / 10,000 l*	1.08 \$
He	99.999%	150 l	166.67 \$ / 10,000 l*	2.50 \$
Total				165.63 \$

This table covers the major ingredients except some pure chemicals used a dopants in negligable quantities, auxiliary materials, and a high-grade silica tube. The most important and probably the only supplier of very high-quality pure silica tubes is Heraeus. Prices range from 80 - 200 US \$* per tube depending an quantity ordered, size, and specification. A price of 200 \$/tube is assumed in the following. The <u>material costs per preform</u> are therefore about 365 \$. The annual costs follow straightforward.

These calculations give a clear picture of material cost structure. The dominant factors are $GeCl_4$, the pure silica tube and pure oxygen.

It is of interest to compare these estimates for a graded index fiber with an estimate for a <u>single mode fiber</u>. In this case $GeCl_4$ would be used in much smaller quantities, e.g. as low as 2% of the graded index case. This would reduce the cost figure/preform by approximately 65 \$/preform to 300 \$, which is little more than 80% of the graded index cost.

Because of tighter tolerances and smaller core sizes involved the overall yield of SM fiber will, however, be smaller than for GI fibers. Compare also Table 4.2 for relative material cost of various fibers.

Labor cost:

According to Section 7.1.9 the following personnel is required for preform production

1 technician as supervisor
2 semiskilled workers operating the glass workers lathes
1 semiskilled worker for tube characterization, screening
1 skilled worker for tube set up
1 unskilled worker

Table 9.3: Wages in preform production (all figures in US $).

	wage/h dayshift	wage/h nightshift	wage/h sunday
technician	15	30	37.5
skilled	10	20	25
semiskilled	8	16	20
unskilled	6	12	15

Using the assumptions on wage level, wage structure (Table 9.3), non-wage labor costs, reserve personnel, the wage bill for preform production can easily be calculated.

The basis of the calculation is cost of one dayshift:

1 technician	8 x 15 $	=	120 $
1 skilled	8 x 10 $	=	80 $
3 semiskilled	3 x 8 x 8 $	=	192 $
1 unskilled	8 x 6 $	=	48 $
Total			440 $

Direct labor costs of one night shift and of one sunday shift are 880 $ and 1100 $ accordingly.

The total labor cost can now be calculated by the simple formula (350 days = 50 sundays + 300 annual working days, 24 hours = 2 dayshifts + 1 nightshift)

2 x 300 x cost of one dayshift
+ 1 x 300 x cost of one nightshift
+ 3 x 50 x cost of one sundayshift

sum x 1.33 (reserve personnel) x 1.5 (non wage labor cost)

which gives labor cost for preform production as 1,383,000 $

Energy consumption is only a small cost factor in preform production. It is calculated from the energy consumption figures of Table 7.3 and an electrical energy price of .055 $ / kWh.

Fiber drawing: The main cost factors in fiber drawing are the costs of the chemicals (acrylates) for coating, labor, electrical energy in descending order of importance.

According to the estimates of Table 7.2, 1.3 kg of acrylate are needed for coating the fiber from one preform (0.25 mm diameter). Assuming a price of 110 US $/kg, coating costs/ preform are 143 $, If 90% of produced preforms (4860 preforms) are processed, approximately 695,000 US $ must be spent on acrylates.

The estimates for energy costs are derived from Table 7.3 using the same price/kWh.

Labor costs calculations use the same schedule as in preform fabrication. For fiber drawing only one additional semiskilled worker/shift is needed. This worker costs 64 $/day-shift, 128 $/night shift, 160 $/sunday shift.

For annual wage cost for fiber drawing we therefore get 201,000 US $.

Quality testing: Quality testing is a very labor intensive production step. The following assumptions are made for the cost calculations.

Time required for testing varies substantially between firms. A careful testing of one spool (2 - 5 km fiber) seems to require 40 - 60 min. Since there are six test stations available, the output of two shifts' preform production and fiber drawing can easily be processed during one shift. So no night, no sunday shifts and no personnel reserve are necessary if two day shifts are made. One day shift consists of 5 semiskilled and 2 highly skilled workers. So the total wage bill for testing is 504,000 US $.

Energy cost is almost negligable, due to very low energy consumption of the testing equipment.

Royalties: Since optical fiber production depends crucially on licenses from leading firms it was necessary to include this factor. Five percent of the fiber selling price is assumed to be a reasonable figure, but not meant as a regulation of seller and buyer.

Miscellaneous: There are a few minor cost factors which have been neglected so far. A lump sum of 10% of the other costs of sales is assumed to cover this factor. It includes some pure chemicals, chemicals for tube cleaning etc.

9.1.4 Expenses

The category "expenses" covers cost factors that do not vary with the scale of production (at least not with minor changes), the so-called fixed cost. In case of fiber production they include depreciation, service costs, personnel overhead, climatization/clean room.

- <u>depreciation:</u> consists of two positions.
  Depreciation of buildings (depreciation factor 0.05)
  Depreciation of machinery and equipment (depreciation factor 0.10). Depreciation is linear, so that buldings are assumed to be utilized 20 years, machinery 10 years.

- <u>clean room conditions, climatization:</u> The airconditioning system including the special installations for the clean rooms are assumed to consume 350 kW on an average, with peak load 1000 kW. This results in annual electrical power cost for this purpose of <u>163,000 US $</u>.

- <u>service cost:</u> a monthly service cost allowance of 0.7% of machinery prices is assumed for the MCVD lathes and the drawing towers. Other service costs are included in the position"miscellaneous".

- <u>overhead personnel cost:</u>
  The administrative staff (shared with the adjacent cable production unit) is assumed to consist of

  1 president of the company
  3 directors + 3 assistants
  3 highly skilled and
  3 semiskilled employees.

  In addition the maintenance of both factories (fiber and cable) requires 3 skilled workers (craftsmen) and 5 unskilled workers (janitors, cleaning personnel). Under the assumptions of Section 9.1.3 and the assumption of one dayshift for this personnel the wage bill of the overhead personnel is <u>930,000 US $</u> per year. Fifty procent of this figure is to be carried by fiber production.

9.1.5 Cost measures of fiber production

It is an interesting exercise to calculate average variable costs (AVC), average fixed costs (AFC), average total costs (ATC), marginal costs from Table 9.1. The calculations are straightforward and the results are presented in Table 9.4 below. The definition of marginal costs in this case is: cost change per produced unit/change of production scale.

Table 9.4. Cost measures of fiber production (in US $).

production scale	VC	AVC*	FC	AFC*	ATC*	MC*
14,300 km	1,415,000	0.0989	2,098,000	0.1468	0.2457	0.0989
28,600 km	2,829,000			0.0734	0.1723	0.1539
43,000 km	5,045,000	0.1173		0.0488	0.1661	0.1493
50,000 km	7,013,000	0.1238		0.0420	0.1658	

*) in US $ per meter

Production scales are chosen to resemble the production scale changes for additional day , night ,and sunday shifts. The ATC figures show strong economies of scale, rising AVC are more than compensated by falling AFC. The high value of marginal costs between 28,600 and 43,000 km/year results from a necessary second shift of the testing people. Over the whole range of sensible output scales,ATC are covered by the assumed fiber price of 0.3 $/m.

9.1.6 Rentability of fiber production

The results of Sections 8.2 and 9.1.1 can be used to get an impression of rentability and its determining factors. To establish the results for the reference production facility standard present value calculations are used.

To arive at reasonable results some additional assumptions are necessary

- on the length of the gestation period of investment, i.e. time necessary to build the factory, install the machines, train the workers and get high quality production running
- profit taxes
- the rate of interest

For the calculations it is assumed that the construction of the factory, installations of machinery and equipment takes one year, and that to train workers and to get high quality production running on maximum scale takes another year. In these two years no income from fiber production is to be expected, but the cost of these activities have to be carried. Afterwards full scale production is assumed for another 9 years, which is consistent with 10% linear depreciation of machinery. No scrap value for the machinery is specified.

A proportional profit tax with a tax rate of 50% and a yearly rate of interest of 10% are assumed. In this case the calculations follow the following scheme:

$$C = \text{investment expenditure} - \text{cost of starting production}\ (1+r)^{-1} + \\ + \sum_{i=2}^{10} (\text{expected net income from operations} \times (1-t))(1+r)^{-i} \qquad (9.1)$$

t ... tax rate

r ... rate of interest

Investment expenditure 10,850,000 US $
Cost of starting production ... FC + 1/2 VC = 5,193,000 US $

The expected net income from operations is taken from the position "earning from operations" of the profit/loss statement, with the following qualifications: to avoid double counting, depreciation is <u>added</u> to the "earnings from operations". Afterwards tax is deducted. The relevant figure, taken as constant over the period in question is therefore 7,715,000 (1 - t) US $ per year.

Equation (9.1) then reads as

C = -10,850,000 US $ - 4,720,000 US $ + 18,922,000 US $ = 3,352,000 US $

This example shows, that interest rates, taxes, yield, and costs of starting production play a crucial role for the profitability of fiber production. A lower tax rate on profits, shorter and cheaper installations periods and lower rates of interest contribute heavily to the profitability of fiber production. Assume, in contrast to the example above, a tax privilege for this reference enterprise of, say, a 25% profit tax rate.

In this case the figures change drastically to

C = -10,850,000 US $ - 4,720,000 US $ + 28,383,000 US $ = 12,813,000 US $

This means that the present value of net income from operations minus the present value of the costs of getting production started exceeds the investment expenditure by 12.9 mill US $, or that after 6 years of operation the plant has financed itself.

Similar examples can be calculated for different assumptions over yields and interest rates. These examples make clear that minor revisions of assumptions concerning wage costs, required personal, consumption and prices of chemicals do not influence the profitability of such an enterprise to the same extent as a simple tax privilege or rising production yields do. In the light of these results it does not make too much sense, do discuss different material and energy requirements of different preform production processes or different fibers, if yield estimates are not reliable and/or tax conditions are not known. Furthermore these results suggest that even investment expenditure is not the most important factor for profitability.

9.2 Cable production

There is a list of obstacles for calculations comparable to those of the last few sections of this paper:

- no generally accepted standards and specifications for optical fiber cables
- cable firms produce customer designed optical cables upon order
- therefore there is no anonymous world market existent, no significant production on inventories.

On the level of a single enterprise, one cannot reasonably calculate profit/loss statements for the production of a standard optical cable, assuming full scale production, because there is simply no market for such an item in the quantities produced. The typical picture is on the contrary, production of a considerable number specifically customer designed cable types in relatively small quantities. This implies long interruptions of production to adjust mechines, and to get the machines running. At least this is the picture the study group formed during its visits at many optical cable producers. All these arguments indicate that there is not much in an attempt to estimate revenue figures for our reference cable production facility.

On the other hand, it is well possible to estimate material costs of the cable described in Section 7.3, so that a major part of the variable costs can be calculated. As indicated above, labor costs, AFC depend on the scale of cable production for which no reasonable assumptions can be specified. Material costs are summarized in Table 9.5.

Table 9.5: Material costs of a 10 fiber cable (US \$/m).

material	g/cm^3	\$/unit	quantity	cost/m
Kevlar 49	1.45	82.5* \$/kg	3.5 cm^3	0.42 \$/m
Petrolate jelly			4.0 cm^3	~0.05 \$/m
Nylon	1.40	9.5* \$/kg	7.8 cm^3	0.10 \$/m
PVC	1.34	4.45* \$/kg	33.0 cm^3	0.20 \$/m
Optical fiber		0.30 \$/m	10 fibers	3.00 \$/m
Total				3.77 \$/m

As these figures clearly indicate, material costs are dominated by fiber costs. Price comparisons between cabled fiber and fiber show ratios ≥2, prices of cabled fiber depending crucially on the number of fibers in the cable, which confirms the result above. The difference between material cost and selling prices covers considerable adjustment costs of the machinery, wages, overhead,ond profit. The profitability of a cabling enterprise depends strongly on the existence of goodmill and a considerable market. Both factors contribute to larger lot sizes in production and help to keep machine adjustment less frequent and adjustment costs low.

Owing to all these arguments no rentability calculations are presented. Calculations of that kind must be performed for an actual enterprise under its market conditions.

9.3 R & D in fiber and optic cable production

Nothing has been said about R & D in this chapter, implicity assuming both production facilities to be factories merely executing production plans. Since fiberoptics and the connected production techniques are still developing very rapidly, R & D is an absolute necessity to avoid product inflexibility and quick obsolescence of machinery and product line. Both factors lead to the ruin of an enterprise in very short time. Some of the visited prominent producers of fibers and cables hold R & D staffs up to 25% of their total employment. Since most of these people are highly qualified, an even larger percentage of the wage bill flows into R & D.

It is immediately clear from the figures in Table 9.1 that AFC will be decisively higher than in the example given, indicating that production must use all available capacity to secure profitability in the short run.

Although R & D cannot be seen as an insurance against unfavorable future developments, but it will strengthen the competitive position of the enterprise.

9.4 Installation: time and cost

As shown in Section 9.3 the gestation period of investment is a crucial factor for profitable production. On the other hand there is ample experience which indicates that installation time and cost are significantly higher in DCs. A central effort in our investigations therefore was the clarification of this issue. Unfortunately there was no success on this point. Most firms denied answering the relevant questions or made installation costs and time dependent on bargaining over concrete contracts.

10. POTENTIAL SUPPLIERS OF EQUIPMENT AND TECHNOLOGY

In the course of this study it became evident that practically all the equipment, raw materials, and semiproducts required to manufacture optical fibers and cables are available on the open market. Potential suppliers of equipment and materials - other than those considered as usual commodities - are listed in the sequel. Additionally a list of companies which are, from our personal knowledge, in principle interested to grant licences and to transfer/sell technology is added.

These lists have been compiled with great care, but completeness cannot, of course, be claimed. Listings are in alphabetical order by common company name; the companies' addresses (head office or division responsible for fiber optics) are to be found in Appendix A.

Raw materials

Pure gases and chemicals	Airco Industrial Gases Apache Chemicals Eagle - Picher Ind. Omiya Chem. Shin-etsu Chem. Stauffer Chemical Synthatron Ventron Wacker-Chemitronic Dynamit Nobel
Coating materials	DeSoto DuPont Toshiba Ceramics
Plastics for cabling	BASF Hoechst
Filling materials (jelly)	BP Chemicals Dussek Campbel

Semiproducts

Quartz tubes	FOI General Electrics Heraeus-Amersil Heraeus Thermal Americal Fused Quartz
Alumina mandrels	Speceram
Preforms	Lightwave Technologies Pilkington Fibre Optic Technologies
Primary-coated fibers	all fiber manufacturers
Kevlar 49 strength members	DuPont

Machinery

Lathes and deposition systems	Canrad Hanovia
	Ferro Technique
	Heathway Machinery
	KDK Fiberoptics
	Litton Engineering Labs.
	Norrsken
	SpecTran
	Wale Apparatus
Gas distribution and mass flow control	Tylan
Drawing towers and furnaces	Artcor
	Astro Industries
	Denton Associates
	Heathway Machinery
	Lepel
Coating and jacketing machines	Formsprag - Webster
	Killion Extruders
	Reel-O-Matic Systems
	RMT Srl
Stranding machines	AFA Industries
	Maillefer
	Rosendahl
	Frisch
Clean rooms	Flow Laboratories
	Seier Helmuth
Fiber thickness monitors	Beta Instrument
Splicing machines	Fujikura
	Furukawa
	Siemens/Siecor
	Sieverts
	Sumitomo

Test equipment

Optical benches and mounts	Newport
Micropositioners	Klinger Scientific
Attenuation meters	Ando Electric
Time domain reflectometers	Anritsu Electric
Bandwidth testers	Fotec
	Hamamatsu
	Hewlett-Packard
	Oi Electric
	Photodyne
	Photon Kinetics
	Quante
	Siemens/Siecor
	Tau-Tron
	Tektronix
	York Technology
Fiber diameter measurement	Anritsu Electric
	Beta Instr.
	Photon Kinetics
	Vickers Instruments
	York Technology

Technology	
Hard-clad silica fibers	American Fiber Optics
	Cabloptic
	CLTO
	Corning
	FOI
	GEC Optical Fibres
	Lightwave Technologies
	NKF Kabel BV
	Northern Telecom
	Phalo/OSD
	Philips
	SEL
	STL
	SpecTran
	Valtec
	Western Electric
	York Techn.
Compound glass fibers	BICC
	Nippon Sheet Glass
	Showa Electric Wire & Cable
	SpecTran
Plastic-clad silica fibers	EOTec
	Pilkington
Plastic/plastic fibers	Mitsubishi-Rayon
	NTT - Ibaraki Electrical Comm.Lab.
	Pilkington
Sol-gel preforms	Hitachi

Cable technology	Belden
	Berkenhoff & Drebes
	BICC
	Cabloptic
	Ericsson
	FOI
	Fujikura
	Furukawa
	NKF
	Northern Telecom
	Optec Daiichi Denko
	Philips
	Pilkington
	SEL
	Siemens/Siecor
	Sumitomo
	Valtec
	Western Electric
	WKM

11. FIBEROPTICS MARKETS: CHARACTERISTICS AND TRENDS

11.1 Objects and applications

To give an impression of current status and trends of fiberoptics markets in seems necessary to give a brief overview of the most important products and give examples for their present applications. These products are fiber, cabled fiber, connectors and couplers, receivers, transmitters, splicing, and test equipment.

One distinguishes usually four markets, although fiberoptic systems use all listed components:

- fiber/cable market: fiber/cabled fiber in many different qualities and specifications
- connector market: connectors and couplers of various types.
- transmitter/receiver market: LEDs, laser diodes, pin-diodes, pinFETs, APDs
- equipment market: splicers, test equipment etc.

Table 11.1 gives a schematic overview over the most important application fields in connection with fiberoptics markets and adds some examples of important installations/ projects.

Long-haul telecommunication fiberoptic systems dominantly use single-mode fiber, splices, laser diodes and pinFETs or APDs. Bit rates of 280 Mbps (TAT-8 Project, Channel-Cross Marseille-Ajaccio) or even higher (North-Eastern Corridor, F-400 M route in Japan) can be achieved with these system configurations; long wavelength transmission at 1,300 nm or 1,500 nm is standard.

Fiberoptics applications for central office interconnects are numerous throughout the industrial world and, up to the recent past, were dominated by multimode fiber, LED - pin (FET)

Table 11.1: Fiberoptics: Applications

Application	Preferred fiber type	Major fiber joints	Sources & detectors	Important installations/ projects
Long-haul telecommunications	single mode	splices	laser; pinFET (APD)	F-400 M route, TAT-8, North-Eastern Corridor, Western corridor Marseille-Ajaccio, Channel-Cross
Central office interconnect	graded index single mode	splices	LED; pinFET LED (Laser); pin diode	Numerous applications in many countries including US, GB, Japan, FRG, France, India, Argentina, Hong-Kong; growing importance of single mode fiber, long wavelength transmission
Short distance (broadband services in subscriber loops, LAN)	graded or step index; (silica and other glass)	connectors	LED; pin-FET or diode	LAN in New York City, Sapporo Subway Control
Very short distance (intra-building, factory, ship, airplane, process control, computer links)	step-index (silica/silica, glass/glass, PCS, plastic/plastic)	connectors	LED; pin diode	numerous different applications

system configurations operating at short wavelength around 850 nm. Recent developments in the US show a growing importance of single mode fiber together with longer wavelength /Hardwick, 1983/. In fact the first single mode central office interconnects are already in operation (Norwich-Sydney, N.Y;/Fiber, Laser News, Febr.3,1984, p.61). Investigations of the study group in Japan revealed a marked trend to SM-fiber for this kind of installation as well as for long haul trunks.

As regards the US, fiberoptic links for central office interconnects are standard, in other industrialized countries they are on the way of becoming usual. From some developing countries applications are also reported (e.g. India/KMI Fiberoptic Market Intelligence, Oct.1983/, Egypt, Argentina).

In short-distance applications one observes a rapid penetration of the market by fiberoptics. Applications range from subscriber loops /Frintrup 1983/, CATV/Samra 1983/, to subway and railway control systems /OITDA 1983/ etc. There is a strong tendency to braodband services: TV, voice, data, facsimile transmitted by the same system. It is contended, that this tendency will also have effects on system design in long distance communication, to allow all these services to be operated through the long-distance telecommunication network, which reinforces the use of highly efficient light waveguides there, too.

Very short distance applications show an even more diversified spectrum in used material as well as in applications. Here PCS and PP fibers come in and may have a market in this area. Applications range from computer links, factory control to aircraft, ship, and building control systems.

11.2 Demand side

This chapter deals with the structure of the demand side of fiberoptics markets and tries to answer the following questions:

- Who are the most important demanders?
- How do they behave?
- Are there different patterns in different countries?

One can say that roughly 60% of fiber and cable markets is in telecommunication, the rest is divided into military, computer interconnect, video and other uses in descending order of importance. This ranking is found in the most important national markets of the US /Kessler 1983/ and of Japan /OITDA 1983/. Similar structures prevail in the industrialized world.

The demand side of the national telecommunication markets is best characterized by the term monopsonistic demand, i.e. one single very powerful demander dominates the demand side. This powerful position is usually taken by the national telecommunication administrations, where they exist.

In the US and in the UK the situation has slightly changed. In the US the Bell system (AT&T) has played very much the role of a national telecommunication authority. After the divestiture of 1.1.1984 patterns have changed. There is now emerging an open market for telecommunication services and some of the most interesting projects in fiberoptics are installed by competitors of AT&T. The most important example in the long haul segment is MCI's fiberoptic Northeast corridor project. A similar development can be observed in the UK where a limited opening of the telecommunication markets can be observed, and where Mercury is establishing itself as a competitor of British Telcom. Again more competition is introduced to the US telecommunication markets on the regional and local level by the opening of these markets to everyone who can cope with the technical standards. In April 1984, the Japanese cabinet decided to lift the monopoly of NTT (Nippon Telephone and Telegraph Public Corporation) and to open "in principle" the national telecommunications market.

Continental European markets are still closed and probably will stay closed. DCs and COMECON countries show the same pattern: national telephone companies or administrations are the sole suppliers of telecommunication services and, as a consequence, the sole (potential or actual) demanders of fiberoptics for telecommunication purposes in these countries.

Traditionally, international projects like the TAT projects or the Channel-cross project are proposed by a consortium of national telephone companies and private investors, who explore the available alternatives for realization and put the chosen one into action.

One important strategy of many national telephone administrations is to rely as much as possible on domestic sources of supply to foster a high degree of national value added. This strategy has not been changed fundamentally in the fiberoptics markets. National telephone companies prefer domestic fibers and cables, if possible. There are cases, where this strategy has led to the development of new fiberoptic industries or branches of these industries. This strategy is even adapted with international projects as the TAT-8 fiberoptic link betwen US and Europe. AT&T will command over 37% of the total capacity of the link and received with 250 mill US $ the largest portion of the 335,4 mill US $ contract. British Telcom (15.5% of the capacity) chose Standard Telephones and Cable, a British affiliate of ITT as their contract partner for the delivery of fiberoptics of 52 mill US $ worth. The same happened in France, where the French National Telecommunications Research Center participated in the R&D efforts of the leading

French firms (CIT-Alcatel, Les Cables de Lyon) to create a national submarine fiberoptic system. This system will, in 1985, connect Ajaccio (Corsica) with Marseille, technical parameters being very close to TAT-8 requirements. In Japan, the three major cable manufacturers team their effort with the Electrical Communication Laboratories of NTT in optical fiber/cable R&D, either jointly (Ocean Cable Co., Ltd.) or bilaterally.

Beyond these general patterns, demand behavior of national telephone administrations differ widely. Some buy complete systems, whereas others prefer to design their systems themselves and buy only the system components, depending on the status of domestic industry.

The next most important market is the military market. It accounts for almost 20% of the whole market volume and offers very important stimula for national suppliers of fiberoptics. By its very nature military markets are national markets and use to be closed for foreign competitors.

The remaining part of the markets consists of a variety of demanders, though, up to the present, pilot installations have dominated the behavior of demanders.

11.3 Supply side

The fiberoptics industry shows a considerable and still growing number of suppliers in all market segments. Since the US markets amount to more than 50% of the international fiberoptics markets it pays to have a close look on them before turning to the situations in other countries. In the US very interesting picture emerges: all main fiberoptics markets (fiber/cable, connectors, receivers/transmitters) are highly concentrated and interconnected via vertically integrated producers.

The most important suppliers of the US market in 1983 and 1984 and their market shares are given in Table 11.2. /Hardwick 1983/.

In both reported years more than 90% of cabled fiber shipments were supplied by only five companies, Western Electric dominating the market with more than 50% market share. The role of Western Electric is somewhat changing since the divestiture of the AT&T system. Until the recent past Western Electric shipped almost every meter of fiber/ cable to the Bell system, a situation that will definitely change. Western Electric is going to engage in the markets outside the Bell system and even in the international markets via AT&T International. Since Western Electric is a very large low-cost producer, all other suppliers must compete with Western Electric in the near future.

Table 11.3 gives a brief account of the degree of vertical integration among fiber/cable suppliers throughout the world. It shows that the majority of firms that produce fiber/cable are in fact vertically integrated. Only 18 out of 93 suppliers make/sell just one item (fiber or cable), all the others engage in other segments of the fiberoptics markets. All major suppliers (excluding Corning Glass Works) are active in more than one market. Corning is a special

Table 11.2: The most important suppliers of the US market in 1983 and 1984 /Hardwick 1983/.

	1983	1984
Western Electric	$ 80 Mill	$ 120 Mill
Siecor	$ 25 Mill	$ 45 Mill
Valtec	$ 10 Mill	$ 15 Mill
Northern Telecom	$ 5 Mill	$ 30 Mill
Anaconda	$ 5 Mill	$ 10 Mill
Others	$ 10 Mill	$ 20 Mill

case, its joint venture with Siemens (Siecor) represents Corning in the other sectors of the market. A large group of firms have an unclear production/selling pattern, i.e. they do not regularly supply fiber/cable <u>and</u> other components.

Table 11.3: Vertical integration among fiber/cable suppliers.

Firm makes/sells	Number
fiber only	6
cable only	12
cable/fiber	20
fiber/other components	3
cable/other components	8
fiber/cable/ other components	14
unclear production/ selling program	30

Besides the US and Canada (Northern Telecom) there are at least seven countries with considerable production capacity in the fiber/cable market: Japan, Great Britain, FRG, France, Sweden, Netherlands, Italy.

In Japan fiberoptic industry cooperates in the Optoelectronic Industry and Technology Development Association including NEC, Hitachi, Fujitsu, Toshiba, Matsushita, Mitsubishi, Oki, Furukawa, Fujikura, Sumitomo, Nippon Sheet Glass as its founders. Japanese suppliers mainly sell on fiberoptic markets in Japan, but undertake strong and successful sales efforts in DCs also (Argentine, India, Singapore,...).

Similar situations, although with institutionally different arrangements, can be found in France, where CNET (Centre National d'Etudes des Telecommunications) coordinates and propagates national fiberoptics efforts. In Germany, where the so called "Kabelkartell" including Siemens, Standard

Elektrik Lorenz, Philips, AEG, Kabelmetall has put its hands on fiber/cable markets. This situation has recently been successfully challenged by Wacker Chemie, a large supplier of chemicals to the semiconductor industry.

The transmitter/receiver market for fiberoptics accounts only for a minor portion of the market for semiconductor devices as lasers, photodiodes, LEDs. In many cases suppliers of complete fiberoptics systems do not produce these devices themselves, in other LEDs can be put to different uses and it is very difficult to estimate the market structure of semiconductor devices used in fiberoptics. The leading US manufacturers are RCA, ITT, Western Electric, Lasertron, General Optronics, the leading Japanese firms are NEC, Fujitsu, Hitachi; Northern Telecom Siemens, CIT/Alcatel, Plessey must be noted as important suppliers outside US and Japan.

Table 11.4: Vertical integration among suppliers of transmitters/receivers and connectors.

	Number
receivers/transmitters only	24
receivers/transmitters/fiber/cable	7
receivers/transmitters/other components	14
receivers/transmitters/fiber/cable/ other components	33
connectors only	25
connectors/fiber/cable	12
connectors/other components	10
connectors/fiber/cable/other components	16

Table 11.4 shows the degree of vertical integration of transmitter/receiver on connector suppliers. The picture in these two markets is somewhat different. The transmitter/receiver market is dominated by suppliers of systems (33),

the connector market shows a larger number of firms (25) who specialize in the connector production, the leading firms not being engaged in all fiberoptics markets.

The reasons for the high degree of vertical integration lie in the behavior of some national telecommunication administrations to demand systems or major parts of systems and in the interest of suppliers. Development of readily usable systems simply makes it easier to sell fiberoptics, since many actual or potential users of fiberoptics are not at all in the position to design and assemble fiberoptic based communication systems themselves at reasonable cost.

Another point to note is the existence of a large number of market niches for specialized producers. Especially in the LAN and very short distance segment of the market many highly specialized fiberoptic systems are supplied. This market characteristic gives new entrants profitable chances.

If one combines behavioral patterns and institutional facts of demand and supply sides in fiberoptics markets a very interesting pattern emerges. In all countries using fiberoptics on a broader scale in telecommunications there exist strong ties between both sides of the markets. The principal demanders of fiberoptic systems and components usually contract with a limited number of suppliers. These suppliers are sometimes affiliated to the demander (AT&T - Western Electric) or cooperate through official, institutional channels (GDR, France, Japan) so that in fact market entrance is severely restricted in several countries. Only in short and very short distance applications an open market exists.

Finally, a list of potential entrants to and drop-outs from the fiberoptic markets is added. This list of recent entrants includes IBM, Kodak, Olympus and N.V. Philips (Valtec takeover), to name the most important ones. The list of dropouts is headed by Times Fiber/Fiber-Laser News, Feb.3,1984/ that almost liquidated its fiberoptics activities.

11.4 Prices in fiber/cable markets

As usual in high technology markets, prices are expected to go down with a higher penetration rate of the technology. This is brought about by economies of scale in the production sphere and by a falling fraction of R&D costs. This is exactly what has been happening in the fiber/cable markets. An excellent example can be found in the decline of Corning prices over the last years, which came down from 3.0 US $ in 1977 to approximately 0.3 US $ per meter of a GI fiber (attenuation: 5 dB/km, 1977; 1.5 dB/km, 1983). This example is shown in Fig.11.1.

Table 11.5 compares 1983 and 1982 fiber prices for different types of fiber for various applications. Unfortunately single mode fiber prices are usually not published, only the graded/step-index fiber prices could adequately be covered by these figures. The official prices for low-volume produced fibers remained constant whereas prices for high performance GI-and SM fibers came down appreciably in the very recent pass. This is a consequence of world-wide expansion of production capacity. Most notably, the ratio of SM to GI fiber prices, which traditionally has been around 3, is approaching values around unity.

It must be stressed that Table 11.5 gives only an indication of the many different prices. Especially GI and SM fibers come in vastly different quality as concerns bandwidth, attenuation, etc. - prices range accordingly up to factor of 4 within one category, say GI.

It is harder to survey cable prices in the same manner as fiber prices. There exists a broad variety of cable specifications as regards fiber specifications, number of fibers used, weight, tensile strength, jacketing etc. Futhermore cables are in most cases not publicly available, so nothing can be said directly about the cable price development. A comparison between fiber and cable prices of the same supplier for indoor cables shows ratios between 3 and 4 between cable and fiber prices and much higher ratios for outdoor cables.

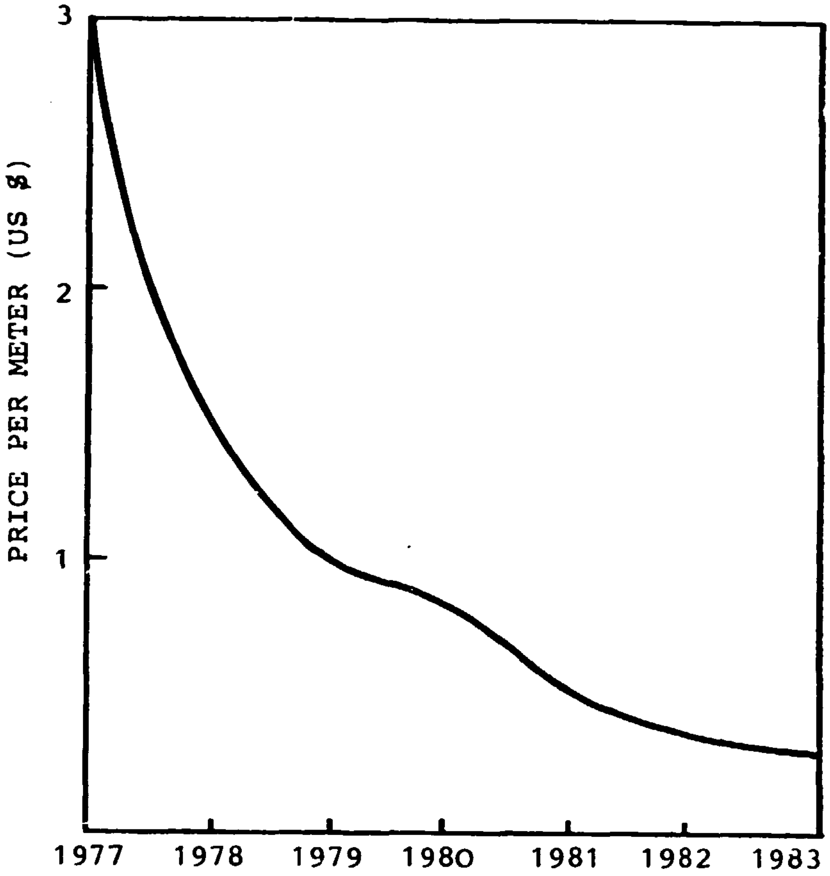

Fig. 11.1: Corning fiber prices 1977-1983
/Kessler 1983/.

Table 11.5: Fiber prices in early 1982 and 1983.

Material	Attenuation	core diameter	cladding	Band width (MHz x km)	Price/m (in US $) 1983	Price/m (in US $) 1982	type
silica	1 dB/1,300 nm	8.2 µ	125 µ		6*)	6	single mode
silica	1.5 dB/1,300 nm	50 µ	125 µ	400	0.31	0.39	graded index
silica	4 dB/820 nm	133 µ	200 µ	20	1.00	1.00	step index
silica	4.5 dB/820 nm	200 µ	300 µ	20	1.50	1.50	step index
glass/glass	15 dB	100 µ	150 µ	10	0.60	0.60	step index
silica/silicone (PCS)	15 dB/850 nm	200 µ	400 µ	40	0.60	0.60	step index
plastic/acrylic	1,200 dB/675 nm	117 µ	128 µ	-	0.013	0.013	step index

Source: Laser Focus'Guide 1982, 1983.

*) The same fiber from the same suppliers costs 1 US $/m per Dec. 1983!

11.5 Market volume projections

It seems convenient to have some figures on already installed fiber km and the perceptions of the study group on market development before proceeding to market projections. Until Dec. 1984 approximately 830 000 fiber km will be installed or on the books in industrialized countries, the US with 650 000 topping the list. Almost 50% of these installations occured or will occur in 1983/1984, US again leading /Schüssler 1983/. Our investigations at European, Japanese, US fiber/cable manufacturers confirm this picture. Many of these producers believe in strong growth of the market in this decade, steepest slope expected for 1988.

Market volume projections for fiberoptics markets are based on valuation and estimate, i.e. they are not really founded on sufficient data and therefore cannot use refined statistical methods. This can be seen from the widely differing estimates of market volumes collected in the recent past by /Kessler 1983/. Our judgement is based on the KMI-market volume projection 1983 /KMI 1983/, and some general considerations on the development of world markets of the communication sector.

The volume of investment in communication throughout the world was around 60 billion US $ in 1980, with a negligible share of fiberoptics. The expected annual growth rate for the 1980's is about 4.5%, so that at the end of the decade approximately 93 billion US $ will be spent on communication investments. The most important technologies competing with fiberoptics are terrestrial microwave transmission, satellites, and traditional copper/coaxial cables. Most experts contend that fiberoptics will drive conventional copper/coaxial cables out of the market by the end of the century. The estimates of the expected split of the long-haul communication market between microwave/satellite and fiberoptics range between 60 : 40 and 50 : 50. The essence of these general considerations is a much higher growth rate for fiberoptics than for the market as a whole. So the annual growth rate for fiberoptics reported by KMI /Kessler 1983/ of 35% seems not to exaggerate the growth of fiberoptics world markets in the 1980's. Japanese producers project their own annual expansion rate at up to 80%/year.

Kessler's findings are based on a careful collection of data on fiberoptics installations and projects. They fit well into the picture drawn by Gnostic Concepts' 1982 projection of worldwide fiberoptic markets /Technology Review May-June 1982/, who predict a somewhat slower expansion.

Table 11.6: World markets for fiberoptics: 1980-1990
(in million US $).

Year	KMI 1983	Gnostic Concepts 1982
1981	177	-
1982	327	335
1986	1 429	1 330
1989	3 044	-
1990	-	2 826

This predictions can be broken down in several ways. One is to find out national shares. Here we see a predominance of the US markets with about 50% of the world market.

The other way is to look for the volume of the market segments listed above. Fiber/cable markets now account for the large bulk of the world markets with approximately 65%, and its share will grow slowly to 75% in the mid 80's. There are two reasons for this increase: (1) increased repeater spacing, which relates to a move to long wavelength transmission, increased use of laser diodes, and single-mode fiber; (2) expected price stability of fiber/cable relative to semiconductor devices and other components.

Connectors/couplers will keep a market share of approximately 5% and the market share of transmitters/receivers will fall from 30% to 21%.

11.6 Markets for DCs

Demand structures and supply/demand interconnections in developed countries constitute severe entry barries for the penetration of the fiber/cable markets in industrialized countries by producers in DCs. Major exceptions are production facilities in DCs owned by established firms and/or joint ventures. The second market for DCs are the domestic markets, hitherto small and of no great importance. If a DC gets fiber and cable production started in the near future the commercial success of this venture depends heavily on domestic telecommunication as primary market /Muraba et al. 1983/. After some time spent on experimentation and system development other DCs could serve as markets. Competition with established firms comes in at this step of development. If further participation in the world market is desired some kind of arrangement with established firms seems absolutely necessary (see Section 13.5.3).

12. POSITION OF DEVELOPING COUNTRIES

The central issue of this chapter is the discussion of advantages and disadvantages of DCs in optical fiber and cable production. Nonetheless the chapter will start with a short note on DCs as demanders of fiberoptics. The position of most DCs is characterized by severe deficiencies in their telecommunication system. It is typically restricted to urban areas, operates only on a very small scale and places severe restrictions not only on economic developments. It is clearly understandable that many DCs make strong efforts to get rid of these obstacles to economic and social development. As a consequence our investigations at the most prominent optical fiber producers in the US, Japan, Europe and our literature studies show up with a list of Latin American (Argentina, Brazil) and Middle and Far East countries (China, Hong-Kong, India, Indonesia, Iraq, Saudi-Arabia, Korea, Singapur, Sri Lanka) which already received or expect shipments of optical fiber, cables and other equipment from developed countries. This list, by no means complete, contains only relatively rich or technologically advanced countries of the third world. This indicates that only the most advanced DCs seem to be capable to install, operate and maintain fiberoptic systemsfor telecommunication purposes. Therefore this narrow subset of DCs will be the most important demanders in the international fiberoptics market in the near future. This reduces the range of DCs to become possible entrants to the fiberoptics market in the next five years to a very exclusive circle.

12.1 Fiber production and DCs

Chapters 7, 8 give a detailed account of material and energy inputs, manpower requirements, general production conditions, capital investment for a 100,000 km/year fiber production facility. The following sections discuss the advantages and disadvantages of optical fiber production in DCs using this production facility.

12.1.1 Material and energy inputs

As one can readily see from Table 7.2, fiber production is not restricted to special location due to some special natural resources. 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. If at all, there is only a small transportation cost disadvantage for DCs. 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 in technical purity, O_2 in very high purity as well as other chemicals in very high purity and minor amounts. Efficient fiber production can only be maintained if these inputs are continuously available. Two systems to assure continuous supply seem viable.

One alternative would be to rely on domestic chemical industry, which holds sufficient stocks of the required chemicals in the required qualities. This system puts the storage costs on the chemical industries, but makes the fiber production facility dependent on the willingness and ability of the chemical industry to deliver the required amounts steadily.

The other system is to hold sufficient stocks of the necessary chemicals and reorder them according to some inventory strategy. In this case, the fiber production firm carries the inventory costs but is somewhat more independent from unreliable sources of supply.

In both cases DCs are worse off than highly industrialized countries. The main reasons for this disadvantage are economies of scale in chemical industry and higher transportation costs if there is no domestic chemical industry. As already earlier noted, optical fiber production uses very similar chemicals as the semiconductor industry. Developed countries with considerable capacities in semiconductor manufacturing can exploit the gain of economies of scale in the production of the required chemicals. Since it is very unlikely that DCs command over substantial capacities in this specialized branch of chemical industries these advantages are not readily accessible for DCs. It is therefore concluded that material costs will be higher in DCs than in industrialized countries.

Electrical energy again must be countinuously supplied to guarantee efficient production and safety in the production facility. One can assume that there are not distinctive disadvantages in the DCs compared with industrialized countries in this respect.

12.1.2 Manpower requirements

The minimum manpower requirements for a 100,000 km fiber/year production facility can be summarized by the following figures

highly skilled technicians	8
skilled workers	4
semiskilled workers	26
unskilled workers	9
craftsmen	3
administrative others	13
	63

There can be no doubt that in the case of a threshold country like Brazil 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. In developed countries, especially in highly industrialized regions qualification requirements do not play a significant role for training costs. Newly hired workers usually command over various skills, which can easily be developed to the skills required.

Training costs, though important for the profitability of a firm,are low compared with a situation of a generally low level of education and skills. Fluctuations of the personnel constitutes a severe problem, if a vacancy due to a quit cannot be filled in reasonable time. The special labor market conditions in many DCs, with high unemployment rates for completely unskilled workers and heavy shortages of trained personnel, makes this problem very likely. That a low level of education and skills reducer productivity is a generally accepted fact.

These problems became 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 advantages are counteracted by the comparably low levels 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.

12.1.3 Capital equipment, technology transfer, research and development

Fiberoptics is a new branch of modern telecommunication industry and is now penetrating industrialized countries. Technological knowledge, patents etc. are in the hands of a few companies. Therefore it is crystal clear 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.

That means that technological knowledge and machinery (including robotics, electronics) and detailed information on processes and their control must be imported from industrialized countries. This is the main disadvantage of DCs. They completely depend on their partners in industrialized countries to get optical fiber production started and keep it running.

The considerations of Chapters 7 - 9 assume a standard size production facility, disregarding the continuous needs for R & D in this field. By now, it should be clear that building up a production facility is little more than a first step towards a self-sustained technological and industrial development. 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.

Cost calculations change profoundly, if one includes R & D. In the short run, this raises overhead costs with only minor effects on production. In the long run many positive effects can be expected:

- development of own machinery and equipment
- better production schedules
- smaller dependency on licensers
- specialization on special fiber designs
- higher yield

All these factors may help to bring down production cost and to reduce the competitive distance to established producers in the long run.

12.1.4 General production and market conditions

Optical fiber production requires special conditions in the factory. These are clean room conditions for fiber drawing and/or preform production, electronically controlled, highly automated gas supplies, climatization, special waste treatment. DCs with adequate industrial experience are not expected to have severe disadvantages in this respect, some countries may be in the position to provide adequate buildings or even partially the necessary equipment from domestic sources.

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 requirement 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.

The advantages of domestic suppliers are connected with the familiarity with the general conditions in the telecommunications sector of their country, language, cooperation with national telecommunication authorities etc. Close cooperation with national telecommunication authorities, universities, national and international companies may provide a nucleus for a national industry as well as the necessary international connections to sell these products not only on domestic markets. The most advanced countries are Brazil, where strong efforts for a national optical fiber production are ongoing since 1974, and Korea, where technology transfer is currently taking place.

12.2 Optical cable production in DCs

Optical cable production uses basically the same equipment as conventional copper cable production. Investment costs to adapt production facilities for optical cable production are quite low, so that conventional cable factories can be used for optical cable production. Such factories exist in a considerable number of DCs, in some cases owned by international companies like Sumitomo's facilities in Brasil and Venezuela.

This disadvantages of labor market conditions in DCs and technology deficits do not count that much as in optical fiber production, since at least parts of the technology are already used in DCs.

In all other respects conditions for cable production are not exceedingly adverse in the most advanced DCs.

12.3 Conclusions

The arguments of the preceeding sections can be summarized as follows. It seems in fact to be possible to produce optical fiber in the most advanced DCs in near future. But one must be aware of the disadvantages with respect to

- supply of highly pure chemicals
- reliable and well trained personnel
- higher training costs
- general production conditions
- participation in international markets
- technological and economic dependency
- size of domestic market

which are by no means outweighted by other factors. Special attention must be paid to the conditions of the necessary technology transfer to avoid the usual unfavorable phenomena.

DCs with little industrial experience cannot meet the requirements for successful optical fiber production, except the case of a complete technology transfer, including manpower and supply of chemicals.

This amounts to invite the construction of a production facility of an established company built up and run under complete domination of this company.

Optical cable production uses equipment very similar to conventional copper cable production and can be put forward at any existing cable factory under reasonable cost.

13. RECOMMENDATIONS

13.1 General considerations

The following recommendations pertain to the central issue of the present study: How can a developing country enter the international fiber/cable market in the most profitable and easiest way? Two aspects will be considered: the purely commercial point-of-view and the socio-cultural implications.

As a starting point, two well-known facts about DC's should be kept in mind:

Developing countries are a highly heterogeneous group. Besides countries on the verge of industrialization ("threshold countries") there are many countries still struggling for development of basic telecom services for their people ("least developed countries"). Evidently, their strategies and positions toward how and whether to introduce fiber optic production will be vastly different.

Several DC are confronted with a "dual economy" situation. Simple rural lifestyles sharply contrast areas of most advanced technology-oriented social patterns.

Several facts about fiberoptic business - which have been partly discussed in previous chapters - will now be put forward as theses.

13.2 Theses about optical fiber/cable production

1. Optical fiber production (OFP) is a rapidly developing high-technology business.

2. OFP is capital investment oriented.

3. Developing countries have little specific advantages for OFP over industrialized countries. Labor cost is only a minor factor, the raw materials required are few, but highly refined.

4. Within DCs , optical fibers have yet to establish their position as a viable transmission medium, in competition with satellites, terrestrial microwave and conventional cable.

5. The market for high-quality fibers is vigorously expanding, low-quality fibers are avaible in surplus quantities.

6. A production facility for OFP should have a capacity of the order of 100,000 fiber kilometers per year to take advantage of economics of scale. Smaller units may not be price-competitive internationally unless specialty fibers are produced.

7. World wide installed OFP capacity is estimated between 2,000,000 and 2,500,000 fiber kilometers per year, which is more than present annual sales.

8. Companies offering optical fiber <u>systems</u> have competitive advantages over companies offering only fibers and/or cables.

9. Setting up an OFP from laying the cornerstone will take about two years until high-quality fibers with high yield can be produced.

10. Comparing fiber production processes, highest value added can be achieved with high-quality silica fibers, produced by the"preform - then drawing"processes.

11. Consistently high quality silica fibers can only be produced by highly automated, computer-controlled machinery.

12. A minimum of 500 manyears have been invested in R & D of today's major production processes.

13. The distribution of value added between fiber and cable is approximately 50:50 (including installation instrumentation/equipment on the cable side).

14. In the field of plastic fibers, there is a single major supplier world-wide that is determined to keep his monopoly. However, even with high market penetration plastic fibers will make up for only a small portion of the telecommunications market, because the lengths involved are rather short.

13.3 Approaches to acquire technology

Table 13.1 shows the principal approaches toward acquisition of a novel technology by a DC. Refering to OFP, independent development would mean that the DC involved develops its own technology from scratch, with no or little outside help. Buying patent licenses means the permission to use patents obtained at low cost from the patent assignee. The bulk of problems in setting up the production would rest with the DC in this scheme. Buying a technology package is understood as a scheme in which a foreign company sets up a production unit in a DC, initializes production, and then turns over ownership and responsibility to a locally owned and controled firm. Joint venture in the sense of this study describes a situation in wich a DC-owned company, being in possession of some relevant technological know-how shares ownership, risk, and profit with a foreign company, which contributes specific fiber optic technology. Import of a complete production plant shall be understood as the construction of a completely new fiber/cable production unit in a DC by a foreign firm, e.g. a multinational company (MNC), retaining control over production and profits.

Table 13.1: Approaches to acquire technology.

		Contribution of DC	Ownership	Profit	Risk for DC
A	Independent development	very high	domestic	if any, domestic	very high
B	Buying patent licenses	high	domestic	if any, domestic	high
C	Buying technology package	medium	domestic	if any, domestic	moderate to high
D	Joint-venture	medium	domestic/ foreign	domestic/ foreign	moderate
E	Import of complete plant	low	foreign	mainly foreign	low

13.1 Recommendations and implications

Carefully weighing the findings of this study we recommend the following strategies for a DC wishing to enter fiber production:

- threshold countries: joint venture, approach D
- least developed countries: import of plant, approach E (conditional recommendation)

Joint venture

This approach requires local existence of relevant know-how. It could be provided by glass-making, chemical, cable, or semiconductor industry. Also, a foreign company granting fiber technology is needed. Economically, this approach seems viable. A problem to be solved by bargaining is to make the enterprise profitable and attractive for the fiber technology investor. This could be achieved e.g. by (temporary) tax privileges, real estate grants, or creation of domestic markets in combination with a telecom policy "buy domestic". "Local technological development" has just evolved as a means of corporate competition between MNCs, a fact which could aid in making the scheme work.

Socio-culturally speaking, the benefits for the DC would lie in a strengthening of its telecom industry, of paramount importance for development of the information society of the future. The general level of technical skills and knowledge would be improved, assisting in implanting an affinity for science and technology. Though only a small number of people might be involved, it is a step in the direction of efforts of industrialization. Glass fibers are a high-technology, high-quality product: familiarity with high-quality products will raise awareness among workers about what high quality is and how it can be produced. If, as required in this scheme, some technology sectors are already in existence, setting up a fiber/cable production would not, in itself, create a dual-economy situation. Finally, a successful joint venture will strengthen the pride and the confidence of the people in their own achievements.

Variant D1: Prepare for joint-venture fiber production

If a developing country should wish to enter fiber production, e.g. because of viewing it as a step in developing its telecom industry, but lacks know-how in one of the relevant technology areas, a long-term strategy is outlined below. This strategy is also highly recommended for approach D (joint venture) as a parallel-track effort, and consists of the following steps, measures, and policies.

- Purchase foreign fiberoptic cables. Train PTT personnel to become acquainted with problems of cable laying, splicing, operation, maintance and repair on a test installation, if necessary with foreign assistance.

- Simultaneouslv set-up of a small research facility, say 20 - 30 people, run and supported by a non-profit organization (or the government).

- Buy a technology license and have the R & D facility implement a small-scale trial production, if necessary with help from foreign personnel. Try out every step of fiber and cable production, starting with jacketing, then cabling of purchased fiber. Proceed to preform making and fiber drawing.

- Develop the chemical industry (which also can serve the semiconductor industry).

- Promote interaction, contact, and mobility between the R & D group and the PTT personnel operating trial installation, in order to raise the state of training and the awareness of problems.

- Protect the infant fiber/cable industry by adequate economic policy measures.

- Develop a domestic demand for fibers and cables.

This approach is a time-consuming one, taking of the order of five years. The inherent strength of this strategy is that a structure of production system is created similar to those of advanced industrialized countries /Oshima 1983/.

Variante D2: Expand existing cable factory

The joint venture can favorably be grouped around a conventional cable factory already operating in a DC. The discussion of approach D and variant D1 applies to this variant by analogy. Many cable companies in industrialized countries have chosen this approach. In search for new products they have either developed or bought fiber technology. Here, we restrict our discussion to the technology transfer alternative.

Concerning profitability, some of the machinery already avaible (stranding machines, extruders, ...) could be used in a modified form. Chances are high that native/qualified personnel is already available that is familiar with some kind of cable-manufacturing technology. Workers should be trained step-by-step for the new technology. If the chemical industry of the DC is unable to supply the necessary quantities of pure chemicals, a cost disadvantage would apply.

If the cable factory is partially owned by a multinational enterprise, it could well be possible that branches in other countries are already in possession of fiber know-how that they might be willing to share.

Existence of a domestic and/or regional market for optical fiber cables would be helpful. The resident cable company would have experience in dealing with such a market. Restrictive policies to shut out foreign competition if so desired - might not be necessary.

As a first step in entering optical fiber business, cables could be made from imported fibers. Technology transfer would take place in the form of a high-technology semi-product, the fiber.

Main advantages are: existing cabling know-how; use of existing machinery, at least in modified form possible; existing business relations with suppliers of cable raw materials; very much relaxed requirements concerning clean-room conditions as compared to fiber production. Risk would be comparatively low, even if fiber import is discontinued or when unexpected technical problems should arise: manufacture of conventional cable could continue. A certain flexibility in producing either cable type could be maintained.

Disadvantages of this approach lie in the dependence on punctual delivery of fibers and their availability in the required quality, and in the fact that shipping costs are incurred.

If the social gains of a DC, touched upon above, can be shown to outweigh the organisational and commercial problems, this variant D2 is definitely recommended.

Import of plant:

This approach would involve import of a complete factory for OFP, including machinery and qualified personnel. The responsibility of setting up the production would rest mainly with the foreign company acting as an entreprenour. Obviously, this is the easiest but not the most profitable way to enter the fiber market, as viewed from the DC involved.

To invite a company to transfer an existing or to construct a new production facility in a DC, tax and/or profit transfer priviliges might be conceded. The share of the value added remaining in the DC would be small, the positive influence on the country's economy limited. The domestic market would probably be served from such a plant, but it would not be very important whether it exists. Finished products would be exported anyway to a high degree. A cost disadvantage of such a company would exist, due to the necessity of import of all raw materials. Whenever the necessity of repair or maintenance would arise, foreign specialists would have to be flown in from abroad.

Postive commercial aspects of this approach are: few requirements concerning the state of development of the DC, other than continous electric energy supply and access to the factory by road, rail, ship or airplane; the factory could be set up in the shortest possible time and take up production fast; capital investment from the side of the DC would be small.

The following socio-cultural implications are foreseen. In developing telecommunications, importing a fiber plant provides an opportunity to leap-frog several technologies and enter into fiberoptics age directly. Prior to a positive decision, a careful case study would have to prove suitability of fiberoptics for the DC under discussion. Any communications medium in a DC (and elsewhere) must fulfill some basic requirements:

- easy maintenance
- high reliability
- adaptability to local conditions
- economy .

Very long repeater spacing and possibility to meet future expansions and development are two important points in favor of optical fibers /Murata et al 1983/.

Compared to many other branches of industry, fiber optics is a clean business with little ecological interference.

Negative aspects are the creation or aggravation of a dual-economy situation; only few workers, mainly unskilled, would get a job in the factory; control of decision would rest with the foreign company.

Altogether, this approach to acquire fiber technology is conditionally recommended for least developed countries.

The other approaches listed in Section 13.3 are discouraged.

Independent development:

Keeping in mind that of the order of 1,000 manyears have been invested in the development of today's production processes each, this is evidently a very costly strategy. Even industrialized countries would be in a difficult position to concentrate a large number of researchers and finance their work. Such a development, started today, would also bear fruit too late to catch a considerable market share.

Buying patent licenses or technology package:

These patterns of technology transfer, though practiced in the past in other branches of industry, do not seem suited for optical fibers and cables. Capital investment would be high as would be the risk. Once the patents or the plant is handed over to the DC owner, all technical problems arising would be his problems. Even experienced management and work force in industrialized countries fight hard to keep quality and yield high.

13.5 Closing remarks

13.5.1 Which technology?

Two facts make it impossible to recommend a single technology for high-quality silica fiber production.

First, the international patent situation is unclear. In the courts of several industrial countries, above all the U.S. (because it has the largest market by far!), vigorous battles are waged for and against the acceptance of claims of patent infringement. Corning Glass Works have a strong patent position in several industrialized countries, but their position remains not unchallenged. Basic patents of glass fiber production will expire around the end of this decade. In DCs the patent situation might be more relaxed, as major technology developing companies have not taken the trouble to file patents in every country.

Second, "the race towards economic manufacturing of high-quality fiber optics is just beginning ... A dominant process, if ever, is not likely to emerge in this decade ..." /Morrow and Schultz 1984/. Hence, in searching for a suitable technology, DCs should not only look for production efficiency, but also for availability and accessibility of this technology. Also, the process to be chosen should have proven flexibility.

13.5.2 PCS fibers

In the course of this study it became evident that the production of the sometimes advocated PCS fibers should be avoided, if production for telecommunications is aimed at. They offer no real cost advantage in production, but can always be plagued by problems arising from water at the silica/plastic interface. If markets for fibers with lower quality (and lower selling price) can positively be defined, all-glass SI fibers made by the double-crucible method are the first choice.

13.5.3 Marketing

A well-defined home market is extremely helpful for starting fiber/cable production. Without it, or without exact as possible predictions of its volume, OFP in a DC might be doomed to premature abortion. Markets in other DCs (regional markets) an in industrialized countries must inevitably be found to keep up production. Penetration of international markets will probably require cooperation with established fiber producers. Since cooperation on technology is a prerequisite for successful OFP this latter requirement is already met.

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Signal Hill, CA 90806, USA

Ando Electric Co. Ltd.
Overseas Sales Div.
Kamata 19-7
4-chome Ota-ku
Tokyo 144, Japan

Anritsu Electric Co. Ltd.
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Appendix B: Glossary

Absorption: In an optical fiber, the lightwave power attenuation due to absorption in the fiber core material.

Acceptance Angle: The angle measured from the longitudinal centerline up to the maximum acceptance angle of an incident ray that will be accepted for transmission along a fiber. The maximum acceptance angle is dependent on the indices of refraction of the two media that determine the critical angle.

Attenuation: The decrease in signal strength along a fiberoptic waveguide caused by absorption scattering and bending loss. This parameter is usually measured in decibels per kilometer. For instance, an attenuation of 3 dB means a reduction of the transmitted power to the half.

Avalanche photodiode (APD): Characterized by the internal amplification of hole-electron pairs that "avalanche" and create additional hole-electron pairs.

Bandwidth: The range of electric signal frequencies within which a fiberoptic waveguide or terminal device performs at a given specification.

Beam divergence: The increase in beam diameter from an optical source, such as a laser or LED, with increasing distance.

Bending loss: Attenuation caused by radiation from the side of a bent fiberoptic waveguide. Bending losses occur when a fiber curves around a restrictive radius and microbends occur when a waveguide is poorly cabled.

Bit-error rate (BER): The fraction of binary digits (bits) transmitted that are received incorrectly. In fiberoptic systems BER is typically 10^{-9}. This means that an average of one bit per one billion sent will be read wrong by the receiver.

Buffer: See fiber jacket.

Cable jacket: The outer protective covering applied over the internal cable elements.

C^3-laser: Cleaved-coupled-cavity laser.

CAD/CAM: Computer-aided design/computer-aided manufacturing.

CATV: Common-antenna television or cable television.

CCTV: Closed-circuit television.

Cladding: The low refractive index material that surrounds the core of an optical waveguide.

Coating of the fiber: The material surrounding the cladding of a fiber. Mostly made from plastic, it protects the fiber from damage.

Coherent light: Light that has the property that at any point in time or space, particularly over an area in a plane perpendicular to the direction of propagation or over time at a particular point in space, all the parameters of the wave are predictable and are correlated.

Concatenation: The process of connecting pieces of fiber to a link, either by splicing or by connectors. The concatenation factor describes the effect of concatenation on bandwidth.

Core: The central primary light-conducting region of an optical fiber, the refractive index of which must be higher than that of the cladding in order for the light waves to be internally reflected or refracted. Most of the optical power is in the core.

talk: The undesired coupling of energy from signals veling on one conductor interfering with signals on nother conductor. Optical waveguides that are intact eliminate crosstalk.

Cut-off wavelength: A single-mode fiber supports only one mode (= the fundamental mode), if the wavelength is longer than cut-off wavelength. Below this wavelength more modes may be guided.

CVD (chemical vapor deposition): Process adapted from semiconductor technology and used to make preforms for drawing optical waveguide.

Dark current: The current that flows in a photodetector when there is no radiant energy or light flux incident upon its *sensitive surface (i.e., total darkness)*.

Data bus: In an optical communication system, an optical waveguide used as a common trunk line to which a number of terminals can be interconnected using optical couplers.

Data bus coupler: In an optical communication system, a component that interconnects a number of optical waveguides and provides an inherently bidirectional system by mixing and splitting all signals within the component.

dBm: A unit for power indicating decibels above or below one milliwatt (mW).

DFB-laser: Distributed-feedback laser.

Double crucible: A process for drawing optical waveguide in which two crucibles are used. The outer crucible contains the cladding glass; the inner crucible contains the core glass. The nozzles of the two crucibles converge at the bottom and fiber is drawn from the melten constituents.

Dopant: A material mixed, fused, amalgamated, crystallized, or otherwise added to another (intrinsic) material in order to achieve desired characteristics of the resulting material. For example, the germanium tetrachloride or titanium tetrachloride used to increase the refractive index of glass for use as an optical-fiber core material.

Edge-emitting LED: A light-emitting diode with a spectral output that emanates from between the heterogeneous layers (i.e. from an edge), having a higher output intensity and greater coupling efficiency to an optical fiber or integrated optical circuit than the surface-emitting LED.

FDM: Frequency division multiplexing.

Fiber core diameter: In an optical fiber, the diameter of the higher refractive index medium that is the primary transmission medium for the fiber.

Fiber diameter: The diameter of an optical fiber, normally inclusive of the core, the cladding, and any adherent coating not normally removed when making a connection.

Fiber dispersion: The lengthening of the width of an electromagnetic-energy pulse as it travels along a fiber; caused by material dispersion due to the frequency dependence of the refractive index by modal dispersion, due to different group velocities of the different modes, and by waveguide dispersion due to frequency dependence of the propagation constant of that mode.

Fiber jacket: Material surrounding the fiber (core, cladding and coating) in order to protect it from physical damage. Sometimes the jacket is in close contact with the fiber (= tight jacket), sometimes a buffer tube allows the fiber to move (= loose tube).

Fiberoptic cable: Optical fibers incorporated into an assembly of materials that provides tensile strength, external protection, and handling properties comparable to conventional electrical cables.

Fiberoptic communications (FOC): Communication systems and components in which optical fibers are used to carry signals from point to point.

Fiber optics: The technology of guidance of optical power, including rays and waveguide modes of electromagnetic waves along conductors of electromagnetic waves in the visible and near-infrared region of the frequency spectrum, specifically when the optical energy is guided to another location through thin transparent strands.

FRP: Fiber reinforced plastics, used as strength members in fiberoptic cables.

Fused Quartz: Crystalline quartz that is melted and cooled to form an amorphous glass. Fused quartz is used to make the tubes for optical waveguide preforms.

Fusion splicer: An instrument that permanently joins two optical fibers by heating and fusing the ends together.

Gallium aluminium arsenide (GaAlAs): The compound used to make most semiconductor lasers that operate at 800 to 900 nanometers in wavelength.

Geometric optics: The optics of light rays that follow mathematically defined paths in passing through optical elements such as lenses and prisms and optical media that refract, reflect, or transmit electromagnetic radiation.

GI-fiber (graded-index fiber): An optical fiber with a variable refractive index that is a function of the radial distance from the fiber axis, the refractive index getting progressively lower away from the axis. This characteristic causes the light rays to be continually refocussed by refraction into the core. As a result, there is a designed continuous change in refractive index between the core and cladding along a fiber diameter.

Infrared (IR): A portion of the electromagnetic spectrum where the wavelength of radiation is between 750 nanometers and 10,000 nanometers. The shorter end of this range is frequently called "near" infrared, and the longer range is called "far" infrared.

Injection laser diode (ILS): A diode operating as a laser producing a monochromatic light modulated by injection of carriers across a p-n junction of a semiconductur having narrower spatial and spectral emission characteristics for longer-range higher-data-rate systems than the LEDs, which are more applicable to larger-diameter and larger-numerical aperture fibers for lower information bandwidths.

Insertion loss: In lightwave transmission systems, the power lost at the entrance to a waveguide, such as an optical fiber or an integrated optical circuit due to any and all causes.

Intermodal dispersion: Dispersion effect in multimode fibers due to optical power running via different waveguide modes.

Integrated optics: The interconnection of miniature optical components via optical waveguides on transparent dielectric substrates, using optical sources, modulators, detectors, filters, couplers, and other elements incorporated into circuits analogous to integrated electronic circuits for the execution of various communication, switching, and logic functions.

Intramodal dispersion: Dispersion effects in a single-mode fiber within this mode.

ISDN: Integrated services digital network.

LAN: Local area network, a non-public data network established for a special purpose and for selected users.

Laser diode: See injection laser diode.

Laser line width: In the operation of a laser, the wavelength range over which most of the laser beam's energy is distributed.

Light: Radiant electromagnetic energy within the limits of human visibility and therefore with wavelengths to which the human retina is responsive. Approximately 380 to 780 nm.

Light-emitting diode (LED): A diode that has applications similar to those of a laser diode. The output power is lower, the limiting modulation rate is lower, but the LED has greater simplicity, tolerance and ruggedness. The spectral width is about 10 times that of a laser diode radiation.

Light source: A generic term that includes lasers and LEDs.

Lightwave communications: That aspect of communications and telecommunications devoted to the development and use of equipment that uses electromagnetic waves in or near the visible region of the spectrum for communication purpose. Lightwave communication equipment includes sources, modulators, transmission media, detectors, converters, integrated optic circuits, and related devices, used for generating and processing lightwaves . The term "optical communications" is oriented toward the notion of optical equipment, whereas the term "lightwave communications" is oriented toward the signal being processed.

Long-wavelength: As applied to fiberoptic systems, this term generally refers to operation at wavelengths in the range of 1,100 nanometers to 1,700 nanometers. Some experimental work in fiberoptic systems is being done at even longer wavelengths-out to 30,000 nanometers.

Material dispersion: Bandwidth limitation due to variable material property in an optical transmission media used in optical waveguides, such as the variation in the refractive index of a medium as a function of wavelength.

MCVD: Modified chemical vapor deposition, inside-tube process for preform fabrication.

Microbending loss: In an optical fiber, the loss or attenuation in signal power caused by small bends, kinks, or abrupt discontinuities in direction of the fibers, usually caused by fiber cabling or by wrapping fibers on drums.

MNC: Multinational company.

Mode: An electromagnetic oscillation that propagates along an optical waveguide; modes are characterized by the distribution and direction of magnetic and electric fields.

Monochromatic light: Electromagnetic radiation, in the visible or near-visible (light) portion of the spectrum, that has only one frequency or wavelength.

Monomode fiber: = Single-mode fiber.

Multimode fiber (MM): An optical fiber that permits the propagation of more than one mode.

Multiplexing: The combining of information signals from several channels into one single optical channel for transmission.

Near infrared: Pertaining to electromagnetic wavelengths from 750 to 3,000 nm.

Numerical aperture (NA): A measure of the light-accepting property of an optical fiber. As a number, the NA expresses the light-gathering power of a fiber. It is mathematically equal to the sine of the acceptance angle. The numerical aperture is also equal to the sine of the half-angle of the widest conical bundle of rays capable of entering a lens, multiplied by the index of refraction of the medium containing that bundle of rays (i.e., the incident medium).

OFP: Optical fiber production.

Optical fiber: A single discrete optical transmission element usually consisting of a fiber core and a fiber cladding. As a light-guidance system (dielectric waveguide) that is usually cylindrical in shape, it consists either of a cylinder of transparent dielectric material of given refractive index whose walls are in contact with a second dielectric material of a lower refractive index, or of a cylinder whose core has a refractive index that gets progressively lower away from the center. The length of a fiber is usually much greater than its diameter. The fiber relies upon internal reflection to transmit light along its axial length. Light enters one end of the fiber and emerges from the opposite end with losses dependent upon length, absorption scattering, and other factors.

Optical transmitter: A source of light capable of being modulated and coupled to a transmission medium such as an optical fiber or an integrated optical circuit.

OTDR: Optical time domain reflectometer, instrument to measure attenuation in fibers.

OVD: Outside vapor deposition.

OVPO: Outside vapor phase oxidation, process for manufacturing fiber preforms.

PCS: Plastic clad silica fiber, a fiber with a silica core and a plastic cladding.

PVCD: Plasma -activated chemical vapor deposition, inside-tube process for preform fabrication.

Photodetector: A device capable of detecting or extracting the information from an optical carrier.

Photodetector responsivity: The ratio of the output current or voltage of a photodetector to the optical power input. In most cases, detectors are linear in the sense that the responsivity is independent of the intensity of the incident radiation. Thus, the detector response in amps or volts is proportional to incident optical power in watts.

Photodiode: A two-terminal device that converts incident light to an electrical current or voltage. The most common types are silicon in which detection is at a p-n junction.

Photon: A quantum of electromagnetic energy. The energy of a photon is h/(c/λ), where h is Planck's constant, c is the speed of light, and λ is the wavelength.

Pigtail: A short length of optical waveguide permanently attached to a light source or photodetector . The pigtail facilitates the use of connectors.

PIN diode: A junction diode doped in the forward direction positive, intrinsic, and negative, in that order. PIN diodes are used as photodetectors in fiber and intetrated optical circuits.

Preform: A tube or rod composed of glass compounds that are inserted into a furnace and from which optical waveguide is drawn.

Pulse Dispersion: A separation or spreading of input optical signals along the length of a transmission line, such as an optical fiber. This limits the useful transmission bandwidth of the fiber. It is expressed in time and distance as nanoseconds per kilometer. Three basic mechanisms for dispersion are the material effect, the waveguide effect, and the multimode effect.

Refraction: The bending of oblique (nonnormal) incident electromagnetic waves or rays as they pass from a medium of one index of refraction into a medium of a different index of refraction, coupled with the changing of the velocity of propagation of the electromagnetic waves when passing from one medium to another with different indices of refraction. The waves or rays are usually changed in direction (i.e., bent) crossing the media interface according to Snell's law.

Refractive index: (1) The ratio of the velocity of light in a vacuum to the velocity of light in the medium whose index of refraction is desired. (2) The ratio of the sines of the angle of incidence and the angle of refraction when light passes from one medium to another. The index between two media is the relative index, while the index when the first medium is a vacuum is the absolute index of the second medium.

RF-MCVD:Radio frequency-enhanced modified chemical vapor deposition.

SDM: Space division multiplexing.

Semiconductor laser: A laser in which lasing action occurs at the junction of n-type and p-type semiconductor materials. Most such lasers used in fiberoptic systems are made of GaAlAs. The wavelength of the emitted light may be varied from 730 nm to 925 nm by varying the aluminum content. The InGaAsP laser emits light at wavelengths from 1,020 nm to 1,700 nm. Semiconductor lasers are size compatible - about the size of a grain of sand - with optical waveguides. The lifetime of these devices is projected to be 100,000 hours.

SI-fiber (Step-index fiber): A fiber in which there is an abrupt change in refractive index between the core and cladding along a fiber diameter, with the core refractive index higher than the cladding refractive index. These may be more than one layer, each layer with a different refractive index that is uniform throughout the layer, with decreasing indices in the outside layer.

Silica: Silicon dioxide, SiO_2. This material occurs naturally as rock crystal, or quartz. When SiO_2 is used as a chemical compound, it is melted and forms fused silica.

Silicon tetrachloride ($SiCl_4$): The major constituent of optical waveguides, $SiCl_4$ is usually furnished as a liquid, and oxygen is bubbled into the container. This results in the formation of a gas that is directed into a fused quartz tube, which (mixed with other gases and oxidized) becomes the preform from which optical waveguide is drawn.

Single-mode fiber (SM): A fiber waveguide that supports the propagation of only one mode. The single-mode fiber is usually a low-loss optical waveguide with a very small core. It requires a laser source for the input signals because of the very small entrance aperture (acceptance cone). The small core radius approaches the wavelength of the source; consequently, only a single mode is propagated.

Sol-gel: Development a low-temperature process for preform fabrication.

Spectral bandwidth: The wavelength interval in which a radiated spectral quantity is a specified fraction of its maximum value. The fraction is usually taken as 50 % of the maximum power level. If the electromagnetic radiation is light, it is the radiant intensity half-power points that are used.

Splice: A nonseparable junction joining one optical conductor to another.

Surface-emitting LED: A light-emitting diode with a spectral output that emanates from the surface of the layers, having a lower output intensity and lower coupling efficiency to an optical fiber or integrated optical circuit than the edge-emitting LED and the injection laser.

TDM: Time division multiplexing.

Total internal reflection (TIR): The reflection that occurs within a substance because the angle of incidence of light striking the boundary surface is in excess of the critical angle.

VAD: Vapor axial deposition, tubeless process for preform fabrication.

VLSI: Very large scale integration.

Waveguide dispersion: The part of the total dispersion attributable to the dimensions of the waveguide since they are critical for modes allowed and not allowed to propagate, such that waveguide dispersion increases as frequency decreases, due to these dimensions and their variation along the length of the guide.

WDM: Wavelength division multiplexing, a technique to exploit to a higher degree the capacity of a fiber by using several light sources emitting light at different wavelengths.

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