

**Optical Fibers – Manufacturing Techniques to Ensure
Low Losses**

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Abstract

Optical fibers are the most popular waveguide for optical transmission. Comparing to other transmission media, optical fibers have a lot of advantages. For example, the information transmission density of an optical fiber cable is 10~100 times higher than that of conventional copper conductor cable. Moreover, it also has a lot of useful applications that can be widely used in many fields, due to its light weight and small size, such as in the military applications, computers. People realized that the optical fibers will become the most economical and important communication system among other communication systems in the distant future.

Optical fiber loss, the scientist most concerned, has surprisingly reduced year after year-20 dB/km in 1970, 0.154 dB/km in 1984. Over a period of ten years, the loss was reduced to 1/100. The intrinsic loss mechanism can be described like absorption by molecular vibration of OH, tailed of infrared adsorption by Si-O coupling, imperfection at connection....etc. By doing various experiments and developing manufacturing techniques, scientists are now able to ensure the low loss of the optical fibers. For widely used in practical information transmission, the optical fiber's loss is needed to be 5 dB/km or less. Scientists now are working hard to enhance the purity of the core in order to perform less loss during the transmission.

As a result, the optical fibers have various usages in message transmission nowadays. Its great merit makes the telecommunication industry an obvious advancement. In this paper, we will describe the basic principle, the properties, the loss mechanisms, and the applications of optical fibers. Moreover, discuss some techniques used to lower the loss of optical fibers.

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I. Introduction

Today, millions of optical fibers are continuing developing communications in the industry. It is a science that deals with the transmission of light through extremely thin fibers of glass, plastic, or other transparent material. Optical fiber has a number of advantages over the copper wire used to make connections electrically ^[1]. For example, optical fiber, being made of glass (or sometimes plastic), is immune to electromagnetic interference, such as is caused by thunderstorms. Also, because light has a much higher frequency than any radio signal we can generate, fiber has a wider bandwidth and can therefore carry more information at one time. Into the depth, optical fibers are transparent, dielectric cylinders surrounded by a second dielectric cylinder, and the light is transported by a serious reflection from wall to wall of an interface between a core and its cladding. Optical fiber is now being vigorously investigated not because it offer a wide frequency band, it offers a widely frequency band at economical costs comparing with other fibers are used, thus taking advantage of its flexibility, small diameter, and low cost ^[14]. Scientist nowadays are working hard to make many developments of optical fibers—ensure low loss, broad bandwidth, and low cost. People realized that the optical fibers will become the most economical and important communication system among other communication systems in the distant future. Although the loss of the optical fiber can be decreased to 0.13 dB/km now ^[2], an even lower loss is the most important project to those scientists for the next generation communication products.

II. Optical Fibers

2.1 The Composition of Optical Fibers

An optical fiber contains three layers : a core made of highly pure glass with a high refractive index for the light to travel, a middle layer of glass with a lower refractive index

known as the cladding which protects the core glass from scratches and other surface imperfections, and an outer polymer jacket to protect the fiber from damage, as shown in Fig. 1^{[17][16]}. Because the core glass needs to have a higher refractive index than the cladding, the core glass is specially chosen. For example, silica glass is doped with a small, controlled amount of an impurity, or dopant, which causes light to travel slower, but does not absorb the light.

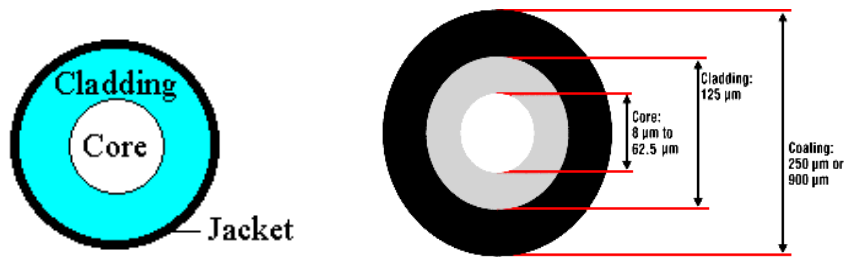


Figure 1. The cross section of an optical fiber.

2.2 Types of Optical Fibers

There are two parameters used to distinguish fiber types, mode and index. The numbers of modes allowed in a given fiber are determined by a relationship between the wavelength of the light passing through the fiber, the core diameter of the fiber, and the material of the fiber. This relationship is known as the Normalized Frequency Parameter, or called V number^[18].

$$V = \frac{2\pi NAa}{\lambda} \quad \text{Equation 1}$$

NA= numerical aperture

a = fiber core radius (microns)

λ = wavelength (microns)

Based on V number, we will have two mode conditions for optical fibers, single mode ($V < 2.405$), and multi-mode ($V > 2.405$). The term index refers to the refractive index of the core material. As shown in Fig. 2^[18], mode and index are used to classify optical fibers into

three distinct groups.

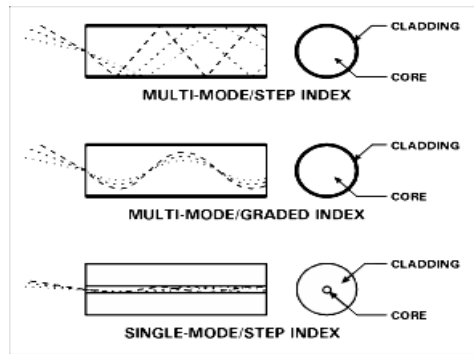


Figure 2. Optical fibers types

2.3 Properties of Optical Fibers

When a light transmits into the fiber, the Snell's Laws is applied (Eq.2) . A light enter a great angle than $\angle a$ are lost and will not reflect. Lights entering at small angle than $\angle a$ are totally reflected, called total internal reflection. Since the core and cladding are constructed from different compositions of glass, theoretically, light entering the core is confined to the boundaries of the core because it reflects back whenever it hits the cladding. For total internal reflection to occur, the index of refraction of the core must be higher than that of the cladding. The total internal reflection phenomenon, as well as the high purity of the core glass, enables light to travel long distances with little loss of intensity. [4]

$$n_a \sin \angle a = n_r \sin \angle r \quad \text{Equation 2}$$

n_a = Index of reflection of air

n_r = Index of reflection of fiber

$\angle a$ = angle of acceptance

$\angle r$ =angle of reflection

The angle of refraction is extremely important in transmission of light beams into optical fibers. In Fig. 3 [4], it can be shown that the angle of acceptance and the angle of reflection in the optical fiber.

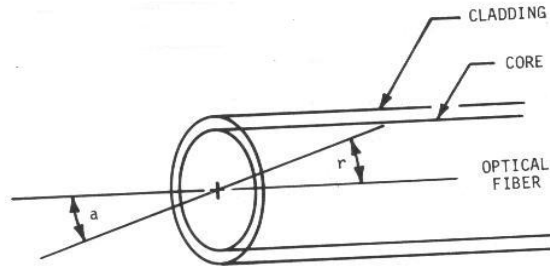


Figure 3. The Snell's Law of an optical fiber.

2.3.1 Numerical Aperture

The angle of acceptance is an angle that represents the half-angle of the cone of acceptance. The mathematical sine of the angle of acceptance is called numerical aperture (NA) which for light entering a air is approximately

$$NA = \sqrt{n_1^2 - n_0^2} \quad \text{Equation 3}$$

Where n_0 is the refractive index of the core and n_1 is the refractive index of the cladding.

2.3.2 Refractive Index

It is a measure of the fiber's optical density. The abrupt differences in the refractive indexes causes the light wave to bounce from core/cladding interface back through the core to its opposite wall (interface) .

2.3.3 Dispersion

In optical fiber systems, dispersion is either intermodal or intramodal^[12]. It is a function of the refractive index of the material and the wavelength or mode of the light traveling through the fiber. It is measured in nanoseconds per kilometer (ns/km) .

2.3.4 Attenuation

Transmission of light by optical fibers is not 100% efficient. Some light is lost, causing attenuation of the signal. Measure of attenuation are made in decibels is defined as^[12] :

$$L(dB) = -10 \log_{10} \left(\frac{P_{out}}{P_{in}} \right) \quad \text{Equation 4}$$

2.3.5 Rise Time

Rise time identifies the fiber's dispersion properties. It is determined by intermode dispersion and/or material dispersion. The overall system rise time can be simply shown as follows^[4] :

$$T = 1.1\sqrt{(T_1^2 + T_M^2 + T_{etc}^2)} \quad \text{Equation 5}$$

where T_1 =intermodal rise time.

T_M =material dispersion rise time.

III. Loss of Optical Fibers

Loss of optical fibers can be caused by many factors. To put into consideration, the loss of the optical fibers can be discussed as follows :

3.1 Absorption of Metal Impurities

The content of a metal ion should be 1 ppb or less. To reach this highly purely material, the Chemical Vapor Deposition (CVD) method is used^{[2][9]}. By using the CVD method, a material is made to react in a vapor phase and deposited. A liquid material can only be vaporized at a fixed temperature and the other impurities in the liquid are let unvaporized. Therefore, the purities of the material become higher in the vapor phase than in the liquid phase when CVD method is applied.

3.2 Absorption of Hydroxyl Group

The content of OH group gives strong absorption loss by vibration coupling with fiber material and dopant material. For example, the absorption loss of OH ion in silica is large at $2.72 \mu\text{m}$ wavelength^[2]. Therefore, the most important thing we have to concern is to prevent the OH ion from entering the fiber during reflection.

3.3 Ultraviolet Absorption and Infrared Absorption

Absorption by the molecular vibration will happen either in ultraviolet or infrared region [16]. When it comes to the widely use glass, silica, the absorption of doped silica glass is changed by the doping element and quantity. When B₂O₃ is used as dopant, for example, loss by it infrared begins around 1.2 μ m and become greater in the long-wavelength band beyond 1.2 μ m. Therefore, the B₂O₃ is not desirable for a fiber for use at 1.3~1.6 μ m band [2].

3.4 Scattering Loss

There are four types of scattering loss for optical fibers : (a) Rayleigh scattering (b) Mie scattering (c) Brillouin scattering (d) Raman scattering [2]. Comparing to Rayleigh scattering, the other three type of scattering loss is small, 1/100 of the Rayleigh scattering loss. So the Rayleigh scattering loss will be mainly discussed here. Rayleigh scattering accounts for the majority (about 96%) of attenuation in optical fiber [2]. It is caused by the transparent materials which have intrinsic spatial density fluctuation. This fluctuation is produced by the fixation of thermal density fluctuation of material at the instance o solidification. The density fluctuation causes the refractive index fluctuation and consequently the Rayleigh scattering. In a word, light travels in the core and interacts with the atoms in the glass. The light waves elastically collide with the atoms, and light is scattered as a result. The attenuation of Rayleigh scattering is shown below [4] :

$$\alpha_R = \left(\frac{8\pi^3}{3\lambda^4} \right) (n^2 - 1) k T \beta \quad \text{Equation 6}$$

where λ denote the wavelength, n the reflective index, k the Boltzmann constant (1.381×10^3 J/K) , T the solidifying temperature, β denote isothermal compressibility. To simplify the equation, the Rayleigh scattering loss can be express by $\alpha_R = \frac{A}{\lambda^4}$; A is the coefficient of Rayleigh scattering loss. The smaller the A value is , the small the value of the Rayleigh

scattering loss α_R . In a silica fiber, the value of A is related to the kind of dopant and the amount of dopant. In Fig.4^[16], it can be clear shown that the scattering loss of an optical fiber.

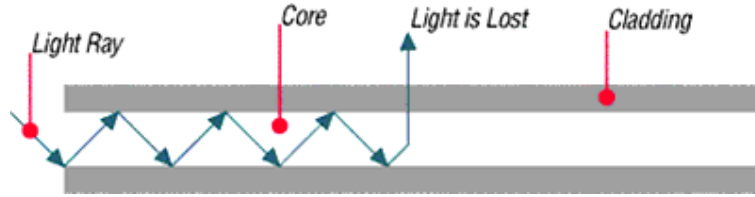


Figure 4. The scattering loss of an optical fiber

3.5 Bending Loss

3.5.1 Macrobending

If a bend is imposed on an optical fiber, strain is placed on the fiber along the region that is bent. The bending strain will affect the refractive index and the critical angle of the light ray in that specific area. As a result, light traveling in the core can refract out, and loss occurs (Fig. 5)^[16]. A macrobend is a large-scale bend that is visible; for example, a fiber wrapped around a person's finger^[7]. This loss is generally reversible once bends are corrected

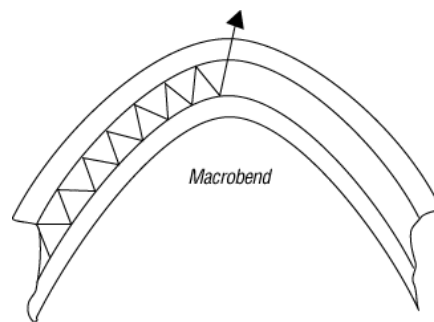


Figure 5. Macrobending of an optical fiber

3.5.2 Microbending

The second extrinsic cause of attenuation is a microbend^[8]. This is a small-scale distortion, generally indicative of pressure on the fiber. Microbending may be related to temperature, tensile stress, or crushing force. Like macrobending, microbending will cause a reduction of

optical power in the glass (Fig. 6.). Microbending is much localized, and the bend may not be clearly visible upon inspection. With bare fiber, microbending may be reversible; in the cabling process, it may not.

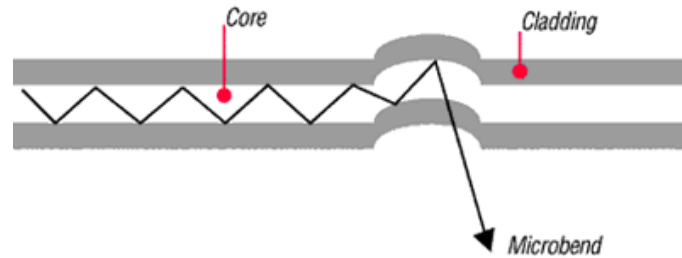


Figure 6. Micro bending of an optical fiber

IV Application of Optical Fibers

Optical fibers are widely used in the early sixties until today. The first commercial applications for fiber optics were medical. Bundled fibers can deliver illumination light to remote regions of the body, and carry coherent images back out to the doctor ^[17]. As a replacement for the rigid Endo-Scope, this became an in-valuable diagnostic tool. It's in communications where fibers have made the most significant advances. Long distance telephone cables, sometimes several inches in diameter and containing hundreds or even thousands of paired wires, have been replaced by a single-fiber cable. Because the light transmitting fiber is immune to electronic noise the fiber can carry thousands more conversations with better sound quality. The optical fiber used in optical telecommunication cables has the capacity of bypassing half-million phone calls or 600 TV digital channels simultaneously. A secret of such capacity is in the cleanliness of the quartz glass used for the optical fiber. The fiber consists of the doped quartz glass core, surrounded by a reflecting cladding of clean quartz glass. The layers protect the fiber from penetration of moisture and aggressive chemical compounds. Cleanliness and various optical behaviors of the cladding and core allow transmitting the light through the fiber at a distance exceeding 300km without

multiplication. A comparison between optical and coaxial cable transmission systems shows that the optical fiber system seems to have large available bandwidth, low attenuation, and low projected cost of transmission medium ^[1]. Another type optical fiber, polymer optical fiber, is used to solve the “last 100m” in data communication ^[11]. It combines the inherently benefits of all optical fibers such as high bandwidth, total electromagnetic immunity with additionally amazing simplicity in handling. These benefit make polymer optical fibers attractive for a widely of applications, such as industrial production line, automotive wiring, and home wiring. Optical fibers are also used in photomultiplier tube (PMT) detection system for optical interrogation of biological samples in microfluidic biochips (Fig. 7) ^[6].

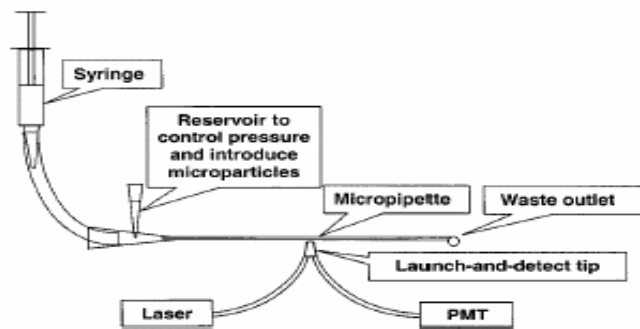


Figure 7. Schematic of the experiment to detect microparticles in flow through a microtype

Also, multiple fibers lay side by side and bonded together at the ends form fiber optic bundles. The end of a fiber bundle can be formed into virtually any two-dimensional shape or outline. Because of this morphological flexibility, fiber bundles are being used for level sensing, part inspection, and process control applications. There are a number of illumination techniques that also take advantage of this unique property. As step-out distance continue to increase, unrepeated electrical communication distances are becoming a limiting factor. Furthermore, it is suggested that using EDFA (Erbium Doped Fiber Amplifier) technology from the telecommunications can industry that provides passive amplification without conversion to an electrical signal, and an appropriate choice of fiber, unrepeated distances of

200-300 km can be achieved ^[19]. These distances will support one of the long-term goals of the tieback community (Fig. 8) .

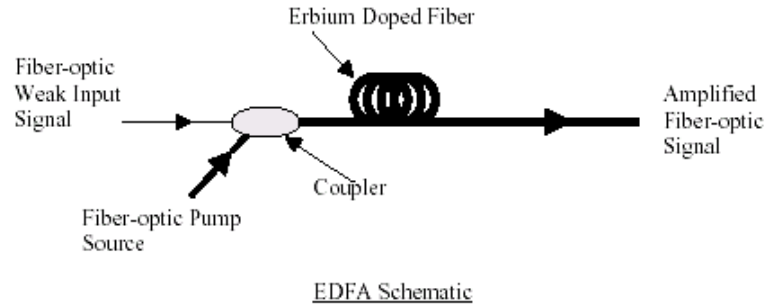


Figure 8. EDFA schematic

The optical fiber can also reach high vacuum system by using Teflon feedthrough ^[10]. A Teflon ferrule with center-drilled holes lightly larger than the fiber diameter replaces the metal ferrules of a standard Swagelok connector. The Swagelok connector when tightened compresses the Teflon to form a vacuum seal for pressures of $\leq 2 \times 10^{-10}$ Torr (Fig. 9.) . The fibers can be easily removed and replaced, and no vacuum sealant is needed. The connectors are inexpensive because they utilize stock fittings.

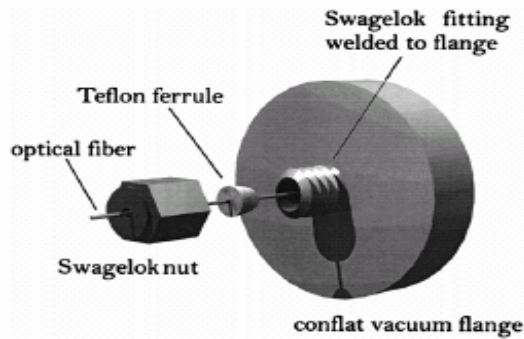


Figure 9. Assembly diagram for the Teflon fiber feedthrough.

In Table 1^[2], it is chiefly shown that how optical fiber could put into practice in information transmission.

TABLE 1 Characteristics and applications of optical fibers

Characteristics	Applications
Low loss and wide bandwidth High density of information transmission	Ordinary telecommunication cables : city trunk cable, video transmission cable, etc
Light weight and small size	Military applications (aircraft, ship, missiles, etc.) , computers.
No electromagnetic induction	Military applications (withstand electromagnetic pulse triggered by nuclear explosion) , railways, area exposed to lightning
High heat resistance	Fire-retardant and heat-resisting wires
No Sparking	Explosion-proof application (oil fields, oil factory, mines, etc)

Scientists today still work hard to reduce optical transmission loss. For example, fluorophosphates optical fibers, it was found that a stable fluorophosphate glass composition can be prepared using optimized processing technologies, and the scattering losses in fibers drawn from this composition can be reduced than those observed in synthetic silica fibers (Fig. 10.) [5].

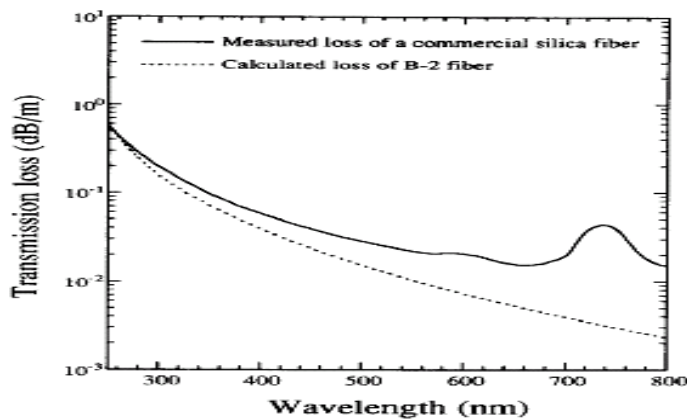


Figure 10. The measured transmission loss spectrum of a commercial silica fiber and the calculated intrinsic loss spectrum of B-2* fiber.

* : B-2 denote one type of fluorosphate optical fibers

Finally, the fastest growing market for fiber optics is intelligent transportation systems,

smart highways with intelligent traffic lights, automated toll booths, and changeable message signs to give motorists information about delays and emergencies.

V Summary and Conclusion

This term paper basically describes the principle, the composition, the property, and the major loss mechanism of optical fibers. It can be clearly shown that some applications are applied due to optical fibers' specific characteristics - less expensive, thinner, higher carrying capacity, no power and no-flammable. Silica is the major glass used in optical fibers because of its lower transmission loss. Since the optical fibers' design and fabrication techniques have shown exceptionally rapid progress, scientists now believe that in the distance future the optical fiber will change dramatically the entire aspect of communications in human society.

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