CHAPTER 3
TRANSMISSION CHARACTERISTICS OF OPTICAL FIBERS

3.1 Introduction

The basic transmission mechanisms of the various types of optical fiber waveguide have been discussed in Chapter 2. However, the factors which affect the performance of optical fibers as a transmission medium were not dealt with in detail. These transmission characteristics are of utmost importance when the suitability of optical fibers for communication purposes is investigated. The transmission characteristics of most interest are those of attenuation (or loss) and bandwidth. The importance of reducing the attenuation has been indicated in Section 1.4. The other characteristic of primary importance is the bandwidth of the fiber. This is limited by the signal dispersion within the fiber, which determines the number of bits of information transmitted in a given time period. Therefore, once the attenuation was reduced to acceptable levels, attention was directed towards the dispersive properties of fibers. Again, this has led to substantial improvements, giving wideband fiber bandwidths of many tens of gigahertz over a number of kilometers.

_ When designing an optical link one of the most interesting questions is the maximum distance between the emitter and detector for a certain bit rate. Two different analyses have to be done:

1. An analysis of the attenuation budget: Which is the maximum distance before the signal is too small and the photodiode cannot detect it? (attenuation limited link)
2. An analysis of the dispersion budget: which is the maximum distance before the optical pulse broadens beyond the value when they overlap? (dispersion limited link)

3.2 Attenuation

The attenuation of a light signal as it propagates along a fiber is an important consideration in the design of an optical communication system, since it plays a major role in determining the maximum transmission distance prior to signal restoration. The basic attenuation mechanisms in a fiber are **absorption**, **scattering** and **radiative** losses of the optical energy. Absorption is related to the fiber material, whereas scattering is associated both with the fiber material and with structural imperfections in the optical waveguide. Attenuation owing to radiative effects

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originates from perturbations (both microscopic and macroscopic) of the fiber geometry. The attenuation or transmission losses of optical fibers has proved to be one of the most important factors in bringing about their wide acceptance in telecommunications. As channel attenuation largely determines the maximum transmission distance prior to signal restoration, optical fiber communications became especially attractive when the transmission losses of fibers were reduced below those of the competing metallic conductors (less than 5 dB km^{-1}).

Signal attenuation within optical fibers, as with metallic conductors, is usually expressed in the logarithmic unit of the *decibel*. The *decibel*, which is used for comparing two power levels, may be defined for a particular optical wavelength as the ratio of the input (transmitted) optical power P_i into a fiber to the output (received) optical power P_o from the fiber as:

$$\alpha_{dB} = \frac{10}{L}\log_{10}\frac{P_i}{P_o} \qquad \textbf{(Equation 3.1)}$$

In optical fiber communications the attenuation is usually expressed in decibels per unit length (i.e. dB km^{-1}). where α_{dB} is the signal attenuation per unit length in decibels, which is also referred to as the fiber loss parameter and L is the fiber length. However, addition and subtraction require a conversion of numerical values which may be obtained using the relationship:

$$\frac{P_i}{P_o} = 10^{(dB/10)} \qquad \textbf{(Equation 3.2)}$$

The attenuation is a function of wavelength, as is shown by the general attenuation curve in Figure 3.1.

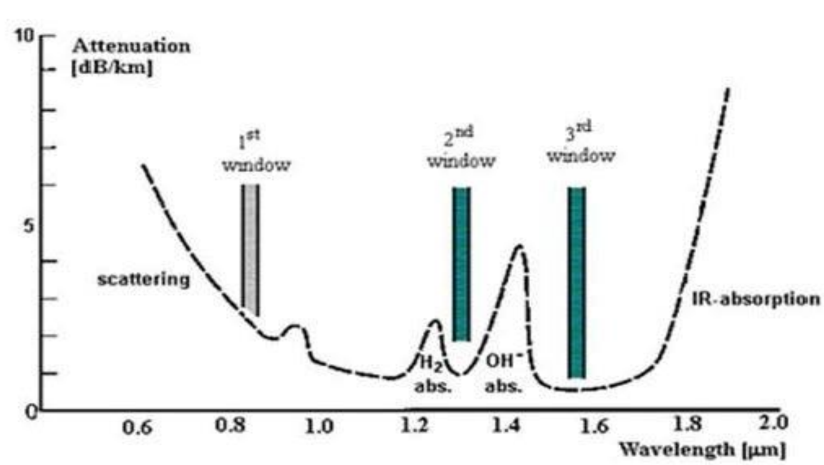

Figure 3.1: Attenuation versus wavelength

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Example 3.1

When the mean optical power launched into an 8 km of fiber is $120\mu W$ and the mean optical power at the fiber output is $3\mu W$. Determine:

a. The overall signal attenuation or loss in decibels through the fiber assuming there are no connectors or splice losses.

b. The signal attenuation per kilometer of the fiber.

c. The overall signal attenuation for a 10 km optical link using the same fiber with splices at 0.5 km intervals, each giving an attenuation of 1 dB.

d. The numerical input/output power ratio in (c).

Solution:

a. Using Equation (3.1), the overall signal attenuation in decibels through the fiber is:

$$\text{Signal Attenuation} = 10\log_{10}\frac{P_i}{P_o} = 10\log_{10}\frac{120\times10^{-6}}{3\times10^{-6}}$$

$$= 10\log_{10}40 = 16\ dB$$

b. The signal attenuation per kilometer for the fiber may be simply obtained by dividing the result in (a) by the fiber length which corresponds to it using **Error! Reference source not found.**) where:

$$\alpha_{dB}L = 16\ dB$$

Hence:

$$\alpha_{dB} = 2\ dB\,km^{-1}$$

c. As $\alpha_{dB} = 2\ dBkm^{-1}$, the loss incurred along 10 km of the fiber is given by: $\alpha_{dB} = 2\times10 = 20\ dB$. However, the link also has nine splices (at 1 km intervals) each with an attenuation of 1 dB. Therefore, the loss due to the splices is 9 dB. Hence, the overall signal attenuation for the link is:

$$\text{Signal Attenuation} = 20 + 9 = 29\ \text{dB}$$

d. To obtain a numerical value for the input/output power ratio, Equation (3.3) may be used where:

$$\frac{P_i}{P_o} = 10^{(dB/10)} = 10^{(29/10)} = 794.3$$

3.2.1 Absorption Losse in Silica Glass Fibers

Absorption is a loss mechanism related to the material composition and the fabrication process for the fiber, which results in the dissipation of some of the transmitted optical power as heat in the waveguide. The absorption of the light can be divided into:

1. Absorption by atomic defects in the glass composition.
2. **Intrinsic** (caused by the interaction with one or more of the major components of the glass).
3. **Extrinsic** (caused by impurities within the glass).

3.2.2 Linear Scattering Losses

Linear scattering mechanisms cause the transfer of some or all of the optical power contained within one propagating mode to be transferred linearly (proportional to the mode power) into a different mode. This process tends to result in attenuation of the transmitted light as the transfer may be in a leaky or radiation mode, which does not continue to propagate within the fiber core, but is radiated from the fiber. *It must be noted that as with all linear processes, there is no change of frequency on scattering (elastic scattering).*

Linear scattering may be categorized into two major types: *Rayleigh* and *Mie* scattering. Both result *from the non-ideal physical properties of the manufactured fiber, which* are difficult and, in certain cases, impossible to eradicate at present.

3.2.2.1 Rayleigh scattering

Rayleigh scattering is the dominant intrinsic loss mechanism in the low-absorption window between the ultraviolet and infrared absorption tails. It results from inhomogeneities of a random nature occurring on a small scale compared with the wavelength of the light. These inhomogeneities manifest themselves as refractive index fluctuations and arise from density and compositional variations which are frozen into the glass lattice on cooling. The compositional variations may be reduced by improved fabrication, but the index fluctuations caused by the freezing are fundamental and cannot be avoided. The subsequent scattering due to the density fluctuations, which is in almost all directions, produces attenuation proportional to $1/\lambda^4$ following the Rayleigh scattering formula. For a single-component glass this is given by:

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F \qquad \textbf{(Equation 3.3)}$$

where γ_R is the Rayleigh scattering coefficient, λ is the optical wavelength, n is the refractive index of the medium, p is the average photo-elastic coefficient, β_c is the isothermal compressibility at a fictive temperature T_F, and K is *Boltzmann's* constant. The afictive temperature is defined as the temperature at which the glass can reach a state of thermal equilibrium and is closely related to the anneal temperature.

Furthermore, the Rayleigh scattering coefficient is related to the transmission loss factor (transmissivity) of the fiber χ following the relation:

$$\chi = \exp(-\gamma_R L) \qquad \textbf{(Equation 3.4)}$$

where L is the length of the fiber. It is apparent from Equation (3.4) that the fundamental component of Rayleigh scattering is strongly reduced by operating at the longest possible wavelength.

Example 3.2

Silica has an estimated affective temperature of 1400 K with an isothermal compressibility of 7×10^{-11} m^2 N^{-1}. The refractive index and the photo-elastic coefficient for silica are 1.46 and 0.286 respectively. Determine the theoretical attenuation in decibels per kilometer due to the fundamental Rayleigh scattering in silica at optical wavelengths of **630, 1000 and 1300** nm. Boltzmann's constant is 1.381×10^{-21} J K^{-1}.

Solution:

The Rayleigh scattering coefficient may be obtained from Equation (3.4) for each wavelength. However, the only variable in each case is the wavelength, and therefore the constant of proportionality of (**Equation 3.3**) applies in all cases. Hence:

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F = \frac{248.15 \times 20.65 \times 0.082 \times 7 \times 10^{-11} \times 1.381 \times 10^{-23} \times 1400}{3\lambda^4}$$

$$= \frac{1.895 \times 10^{-28}}{\lambda^4}\ \text{m}^{-1}$$

At a wavelength of 630 nm:

$$\gamma_R = \frac{1.895 \times 10^{-28}}{0.158 \times 10^{-24}} = 1.199 \times 10^{-3}\ m^{-1}$$

The transmission loss factor for 1 kilometer of fiber may be obtained using (**Equation 3.4**):

$$\chi = \exp(-\gamma_R L) = \exp(-1.199 \times 10^{-3} \times 10^{3}) = 0.301$$

The attenuation due to Rayleigh scattering in decibels per kilometer may be obtained from (**Equation 3.1**) where:

$$attenuation = 10 \log \left(\frac{1}{\chi}\right) = 10 \log(3.322) = 5.2\ dB\,km^{-1}$$

3.2.2.2 Mie scattering

Linear scattering may also occur at inhomogeneities which are comparable in size with the guided wavelength. These results from the non perfect cylindrical structure of the waveguide and may be caused by fiber imperfections such as irregularities in the core–cladding interface, core–cladding refractive index differences along the fiber length, diameter fluctuations, strains and bubbles. When the scattering inhomogeneity size is greater than λ/10, the scattered intensity which has an angular dependence can be very large. The scattering created by such inhomogeneities is mainly in the forward direction and is called Mie scattering. Depending upon the fiber material, design and manufacture, Mie scattering can cause significant losses.

The inhomogeneities may be reduced by:

(a) Removing imperfections due to the glass manufacturing process;

(b) Carefully controlled extrusion and coating of the fiber;

(c) Increasing the fiber guidance by increasing the relative refractive index difference.

By these means it is possible to reduce Mie scattering to insignificant levels.

3.2.3 Nonlinear Scattering Losses

Optical waveguides do not always behave as completely linear channels whose increase in output optical power is directly proportional to the input optical power. Several nonlinear effects occur, which in the case of scattering cause disproportionate attenuation, usually at high optical power levels. This nonlinear scattering causes the optical power from one mode to be transferred in either the forward or backward direction to the same, or other modes, at a different frequency. It depends critically upon the optical power density within the fiber and hence only becomes significantly above threshold power levels. The most important types of nonlinear scattering within optical fibers are stimulated Brillouin and Raman scattering, both of which are usually only observed at high optical power densities in long single-mode fibers.

These scattering mechanisms in fact give optical gain but with a shift in frequency, thus contributing to attenuation for light transmission at a specific wavelength. However, it may be noted that such nonlinear phenomena can also be used to give optical amplification in the context of integrated optical techniques.

3.2.3.1 Stimulated Brillouin Scattering

Brillouin scattering was first demonstrated by Léon Brillouin, who theoretically predicted light scattering from thermally excited acoustic waves in 1920 [1]. In 1930 it has been experimental demonstrated by E. Gross using a lamp as the light source [2]. After the invention of lasers, the SBS was observed in optical fiber in 1972 [3], and it has been studied extensively since then because of its implications for optical communication systems. Although the scattering cross section of the Brillouin Stokes wave is quite low, but in a nonlinear medium like the optical fiber, it can propagate to a long distance with insignificant attenuation. At a certain pump power, this nonlinear scattering becomes stimulated and known as SBS which is strongly dependent on the pump power.

Basic Concept

The underlying physical mechanism of the Brillouin scattering is the transformed of an incident light into a scattered photons and thermal phonons. The scattered wave is propagating in opposite direction to the incident light and it has a frequency downshift set by the nonlinear medium. It is called a Stokes wave which found by George G. Stokes in 19th century [4].

The most distinct origin of the SBS is a physical phenomenon known as electrostriction [5]. Through this phenomenon, the backscattering Stokes interferes with the input pump wave and creates an acoustic wave. Significantly, the propagating wave generates a moving density grating from which it scatters in the opposite direction. The frequency downshift of the Brillouin Stokes can also be attributed by the Doppler effects. The light scattering mechanism is schematically shown in Figure 3.2. Both amplitude of the acoustic wave and the interference pattern are directly proportional with the intensity of the Stokes wave. The acoustic wave in the forward direction works as a Bragg grating, which scatters even more wave in backward direction.

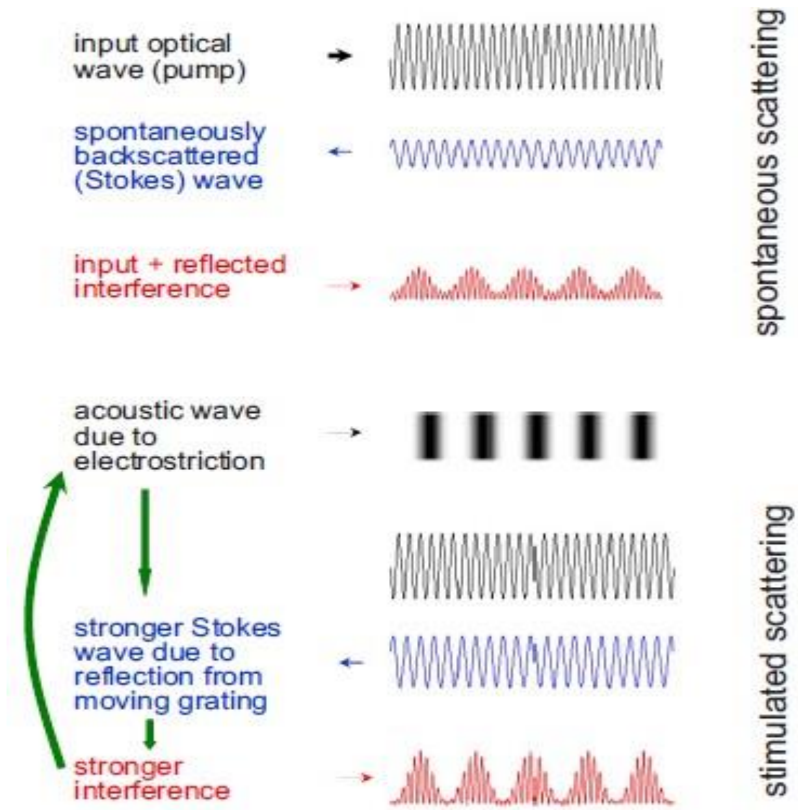

Figure 3.2: SBS light scattering mechanism [4].

The frequency shift is a maximum in the backward direction, reducing to zero in the forward direction, **making SBS a mainly backward process**. Brillouin scattering is only significant above a threshold power density P_B is given by:

$$P_d = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dd} \nu \quad \textbf{(Equation 3.5)}$$

where d and λ are the fiber core diameter and the operating wavelength, respectively, both measured in micrometers, α_{dB} is the fiber attenuation in decibels per kilometer and ν is the source bandwidth (i.e. injection laser) in gigahertz. The expression given in (**Equation 3.5**) allows the determination of the threshold optical power which must be launched into a single-mode optical fiber before SBS occurs.