Optical losses

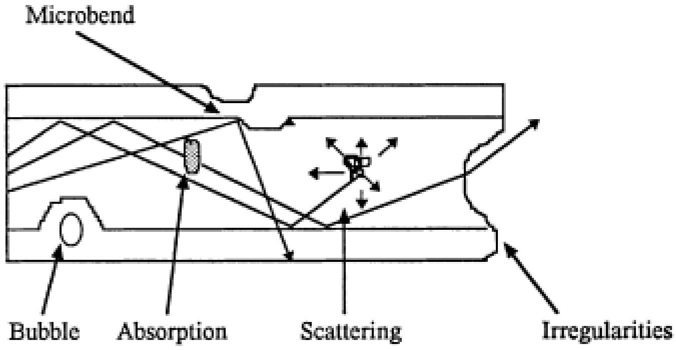
Extrinsic Fiber Losses

These losses are specific to geometry and handling of the fibers and are not functions of the fiber material itself. There are three basic types:

- bending losses
- launching losses
- connector losses

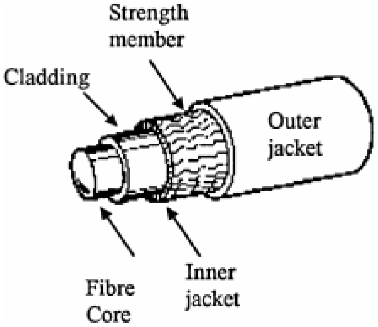
Bending Losses

Bending losses are the result of distortion of the fiber from the ideal straight-line configuration. While the light is traveling inside the fiber, part of the wave front on the outside of the bend must travel faster than the part of the smaller inner radius of the bend. Since this is not possible, a portion of the wave must be radiated away. Losses are greater for bends with smaller radii, particularly for kinks or micro-bends in a fiber. An important cause of attenuation is due to micro-bending of the fiber. Micro-bending is due to irregularly distributed undulations in the fiber with radii of curvature of a few millimeters and deviations from the mean line of a few micrometers, as exemplified in Figure(1).



Fig(1)

Micro-bends arise from mechanical tensile forces by which the fiber is pressed against a rough surface. Although the effect of variations in diameter can be discussed at length by waveguide theory, here it will be sufficient to say that those components of the light that are traveling in the fiber near its acceptance limit cross outside this boundary and are lost from the fiber. These losses may be avoided by careful cable constructions, avoiding excessive mechanical forces, and controlling the temperature variations of the cable. This is achieved by a loose encasing of the fiber in a plastic sheath or by covering the fiber with soft flexible material, as shown in Figure(2).



Fig(2)

Launching Losses

The term launching loss refers to an optical fiber not being able to propagate all the incoming light rays from an optical source. These occur during the process of coupling light into the fiber (e.g., losses at the interface stages). Rays launched outside the angle of acceptance excite only dissipative radiation modes in the fiber. In general, elaborate techniques have been developed to realize efficient coupling between the light source and the fiber, mainly achieved by means of condensers and focusing lenses. The focused input beam of light needs to be carefully matched by fiber parameters for good coupling.

Equally, once the light is transmitted through the fiber, output fiber characteristics must also match the output target characteristics to be able to couple the largest proportion of the transmitted light. This can be done by a suitable focusing lens arrangements in the output end.

There are also initial face (Fresnel) losses due to reflections at the entrance aperture. The Fresnel losses are greater if the fiber/source is air coupled. Hence, most optical couplings to a fiber utilize index matching materials, thus reducing coupling loss substantially.

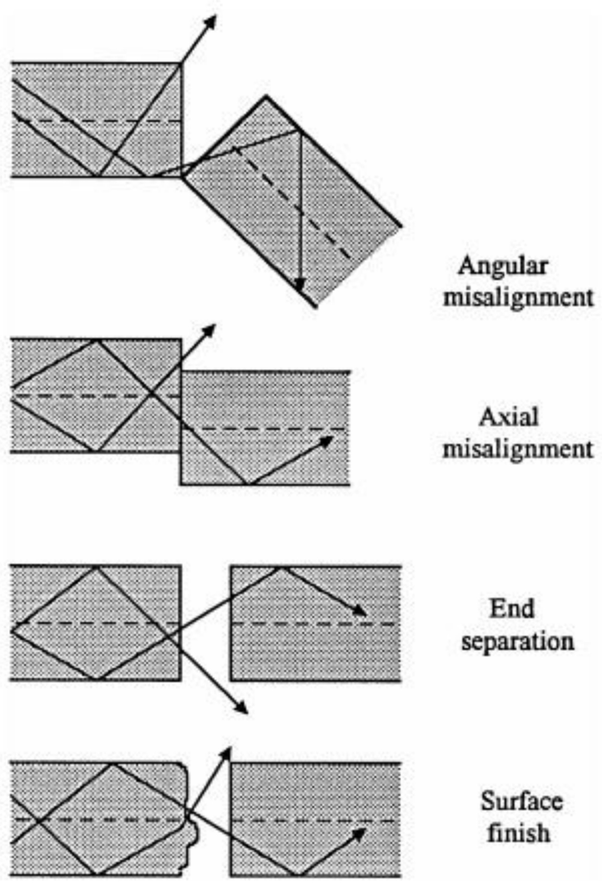
Connector Losses

Connector losses are associated with the coupling of the output of one fiber with the input of another fiber, or couplings with detectors or other components. The significant losses may arise in fiber connectors and splices of the cores of the joined fibers having unequal diameters or misaligned centers, or if their axes are tilted. Mismatching of fiber diameters causes losses that can be approximated by –10 log(d/D). There are other connection losses such as offsets or tilts or air gaps between fibers, and poor surface finishes. Some of these are illustrated in Figure (3).

To take full advantage of fiber characteristics in transmission systems of very low intrinsic attenuation, the contribution of losses from other sources must also remain very small. The attenuation as (d) due to coupling efficiency may be expressed as:

$$\mathbf{a_s(d) = -10\ dB\ \log\eta(d)}$$

where h(d) is the coupling coefficient.



Fig(3)

In general, the positions and shapes of the fiber cores are controlled to tight manufacturing tolerances. Fibers having attenuations greater that 1 dB/km are rarely used in communication networks. Nevertheless, the attenuation of badly matched fibers may exceed 1 dB/km per connector or splice if they are badly handled during installation stages. A good coupling efficiency requires precise positioning of the fibers to center the cores. The simplest way to avoid connector losses is by splicing the two ends of the fibers permanently, either by gluing of by fusing at high temperatures. Losses in gaps can be viewed as a type of Fresnel loss because existing air space introduces two media interfaces and their associated Fresnel reflection losses. In this case, there are two major losses to be considered. The first loss takes place in the inner surface of the transmitting fiber, and the second loss occurs due to reflections from the surface of the second fiber. One way of eliminating these losses is by introducing a coupler that matches the optical impedances of the two materials. This arrangement results in matched reflection coefficients, which is analogous to matching of impedances.

Intrinsic Fiber Losses

Intrinsic fiber losses are those associated with the fiber optic material itself, and the total loss is proportional to length L. Once inside the fiber, light is attenuated primarily because of absorption and scattering; therefore, these are the primary causes of the losses.

Absorption Losses

As in the case of most transitive systems, light loss through absorption in an optical fiber tends to be an exponential function of length. Absorption loss is caused by the presence of impurities such as traces of metal ions (e.g., Cu2+, Fe3+) and hydroxyl (OH–) ions. Optical power is absorbed in the excitation of molecular vibrations of such impurities in the glass, as illustrated in Figure 59.3. One characteristic of absorption is that it occurs only in the vicinity of definite wavelengths corresponding to the natural oscillation frequencies or their harmonics of the particular material. In modern fibers, absorption losses are almost entirely due to OH–1 ions. The fundamental vibration mode of these ions corresponds to l = 2.73 µm and the harmonics at 1.37 and 0.95 µm. It is possible to employ dehydration techniques during manufacturing to reduce presence of OH1 ions. Unlike scattering losses, which are relatively wideband effects, absorption losses due to each type of impurity act like a band-suppression filter, showing peak absorption at well defined wavelengths.

Scattering Losses

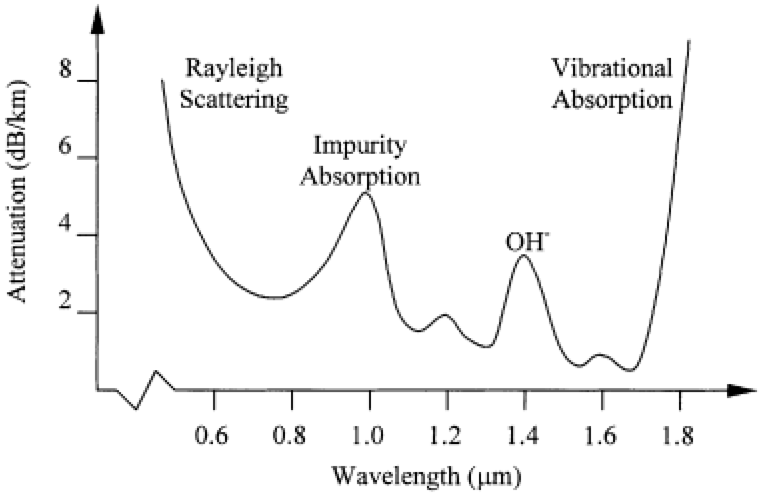
Despite the careful manufacturing techniques, most fibers are inhomogeneous that have disordered, amorphous structures. Power losses due to scattering are caused by such imperfections in the core material and irregularities between the junction and cladding as shown in Figure(3) . Inhomogeneities can be either structural or compositional in nature. In structural inhomogeneities, the basic molecular structure has random components, whereas, in compositional inhomogeneity, the chemical composition of the material varies. The net effect from either inhomogeneity is a fluctuation in the refractive index. As a rule of thumb, if the scale of these fluctuations is on the order of l/10 or less, each irregularity acts as a scattering center. This is a form of Rayleigh scattering and is characterized by an effective absorption coefficient that is proportional to λ^{-4}. Rayleigh scattering can be caused by the existence of tiny dielectric inconsistencies in the glass. Because these perturbations are small with respect to the waves being propagated, light striking a Rayleigh imperfection scatters in all directions. Scattering losses are less at longer wavelengths, where the majority of the transmission losses are due to absorption from impurities such as ions. Rayleigh scattering losses are not localized, and they follow a distribution law throughout the fiber. However, they can be minimized by having low thermodynamic density fluctuations. A small part of the scattered light may scatter backward, propagating in the opposite direction. This backscattering has important characteristics and may be used for measuring fiber properties. Usually, the inhomogeneities in the glass are smaller than the wavelength l of the light. The scattering losses in glass fibers approximately follow the Raleigh scattering law; that is, they are very high for small wavelengths and decrease with increasing wavelength. In general, optical losses in the glass cause the optical power in a fiber to fall off exponentially with the length L of the fiber,

$$P(L) = P(0)\ 10^{-\frac{aL}{10dB}}$$

where P(0) = optical power that couples to the fiber, P(L) = power remaining after length L, and a is the attenuation coefficient indicating the rate of loss of optical power in dB/km. The product aL is called the attenuation of the fiber. An attenuation of 10 dB means that the optical power P(L) at the end of the fiber is only 10% of the initial power P(0). A 3-dB attenuation gives 50%, and 1 dB is about 80%. A typical attenuation coefficient a against wavelength l is shown in Figure (4) for common low-loss fused silica fiber. The optical losses for wavelengths below 1 µm are mainly due to Rayleigh scattering. At larger wavelengths absorption losses are important, notably at 1.4 µm through absorption by OH^{-1} ions. Above 1.6 µm, absorption due to impurities becomes dominant. Because of attenuations, only limited wavelength ranges are appropriate for optical data transmission. Although intrinsic fiber losses can be associated with the core index nf , the core index has an important role in determining the propagation time delay of optical signals. The propagation time delay tp may be expressed by

$$\mathbf{tp = \eta_f\ L/c}$$

where c = velocity of light in the fiber, and L = fiber length. Another type of loss in optical fibers occurs due to the propagation of light at different angles. Light propagating at shallow angles is called low-order mode, and light propagating at larger angles is called high-order mode. For a given length of fiber, the high-order modes reflect more often and cover longer distances than the low-order modes. Therefore, high-order modes suffer more losses, thus causing modal dispersions. The modal dispersion is one of the primary cause of rise time degradation for increasing fiber wavelengths. In addition, propagation time varies with index of refraction, so different wavelength components of the source spectrum have different travel times, thus causing chromatic dispersion.



Fig(4)

Linear scattering losses

Through this mechanism a portion/total optical power within one propagating mode is transferred to another. Now when the transfer takes place to a leaky or radiation mode then the result is attenuation. It can be divided into two major categories namely Mie scattering and Rayleigh scattering.

- **Mie Scattering**

  Non perfect cylindrical structure of the fiber and imperfections like irregularities in the core-cladding interface, diameter fluctuations, strains and bubbles may create linear scattering which is termed as Mie scattering.
- **Rayleigh Scattering**

  The dominant reason behind Rayleigh scattering is refractive index fluctuations due to density and compositional variation in the core. It is the major intrinsic loss mechanism in the low impedance window. Rayleigh scattering can be reduced to a large extent by using longest possible wavelength.

Non linear scattering losses

Specially at high optical power levels scattering causes disproportionate attenuation, due to non linear behaviour. Because of this non linear scattering the optical power from one mode is transferred in either the forward or backward direction to the same, or other modes, at different frequencies. The two dominant types of non linear scattering are :

a) Stimulated Brillouin Scattering and
b) Stimulated Raman Scattering.