Attenuation

The attenuation or transmission loss 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 determined 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:

$$\text{Number of decibels (dB)} = 10 \log_{10} \frac{P_i}{P_o} \tag{2.1}$$

This logarithmic unit has the advantage that the operations of multiplication and division reduce to addition and subtraction, while powers and roots reduce to multiplication and division. However, addition and subtraction require a conversion to numerical values which may be obtained using the relationship:

$$\frac{P_i}{P_o} = 10^{(dB/10)} \tag{2.2}$$

In optical fiber communications the attenuation is usually expressed in decibels per unit length (i.e. dB km^{-1}) following:

$$\alpha_{dB} L = 10 \log_{10} \frac{P_i}{P_o} \tag{2.3}$$

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. A number of mechanisms are responsible for the signal attenuation within optical fibers. These mechanisms are influenced by the material composition, the preparation and purification technique, and the waveguide structure. They may be categorized within several major areas which include material absorption, material scattering (linear and nonlinear scattering), curve and microbending losses, mode coupling radiation losses and losses due to leaky modes.

Material Absorption Losses in Silica Glass Fibers

Material 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 may be intrinsic (caused by the interaction with one or more of the major components of the glass) or extrinsic (caused by impurities within the glass).

1. Intrinsic Absorption

An absolutely pure silicate glass has little intrinsic absorption due to its basic material structure in the near-infrared region. However, it does have two major intrinsic absorption mechanisms at optical wavelengths which leave a low intrinsic absorption window over the 0.8 to 1.7 μm wavelength range, as illustrated in Figure 2.1, which shows a possible optical attenuation against wavelength characteristic for absolutely pure glass.

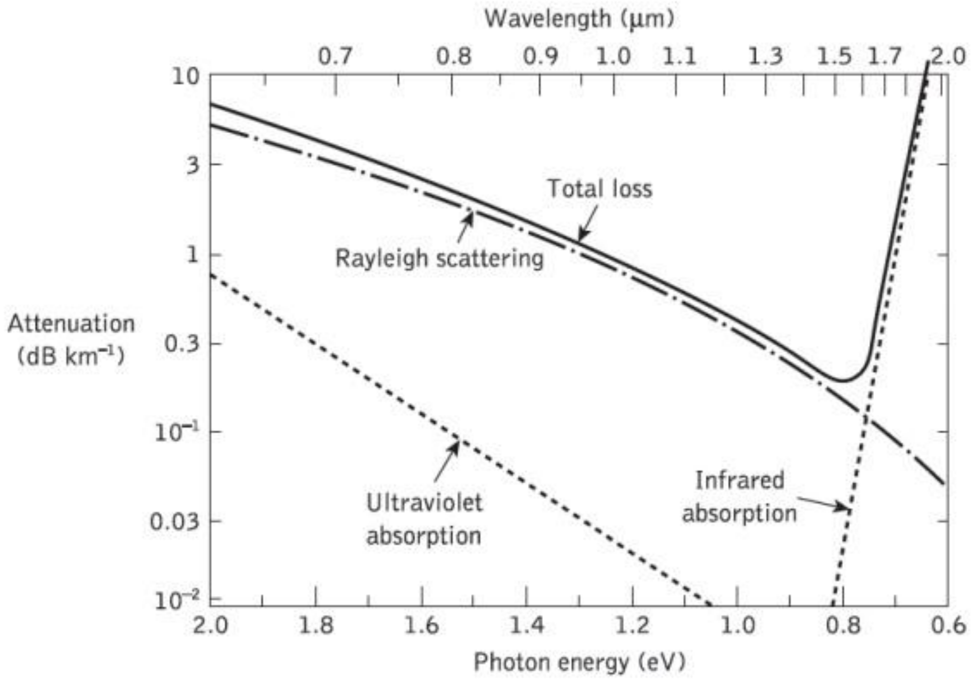

Figure 2.1 The attenuation spectra for the intrinsic loss mechanisms in pure GeO2–SiO2 glass

[Source: htpp://img.brainkart.com]

It may be observed that there is a fundamental absorption edge, the peaks of which are centered in the ultraviolet wavelength region. This is due to the stimulation of electron transitions within the glass by higher energy excitations. The tail of this peak may extend into the window region at the shorter wavelengths, as illustrated in Figure 2.1. Also in the infrared and far infrared, normally at wavelengths above 7 μm, fundamentals of absorption bands from the interaction of photons with molecular vibrations within the glass occur.

These give absorption peaks which again extend into the window region. The strong absorption bands occur due to oscillations of structural units such as Si–O (9.2 μm), P–O (8.1 μm), B–O (7.2 μm) and Ge–O (11.0μm) within the glass. Hence, above 1.5 μm the tails of these largely far-infrared absorption peaks tend to cause most of the pure glass losses. However, the effects of both these processes may be minimized by suitable choice of both core and cladding compositions. For instance, in some non oxide glasses such as fluorides and chlorides, the infrared absorption peaks occur at much longer wavelengths which are well into the far infrared (up to 50 μm), giving less attenuation to longer wavelength transmission compared with oxide glasses.

2. Extrinsic Absorption

In practical optical fibers prepared by conventional melting techniques, a major source of signal attenuation is extrinsic absorption from transition metal element impurities.Some of the more common metallic impurities found in glasses are shown in the Table 2.1, together with the absorption losses caused by one part.

Table 2.1 Absorption losses caused by some of the more common metallic ionimpurities in glasses, together with the absorption peak wavelength

	Peak wavelength (nm)	*One part in 10^9 (dB km^{-1})*
Cr^{3+}	625	1.6
C^{2+}	685	0.1
Cu^{2+}	850	1.1
Fe^{2+}	1100	0.68
Fe^{3+}	400	0.15
Ni^{2+}	650	0.1
Mn^{3+}	460	0.2
V^{4+}	725	2.7

[Source: htpp://img.brainkart.com]

It may be noted that certain of these impurities, namely chromium and copper, in their worst valence state can cause attenuation in excess of 1 dB km−1 in the near-infrared region. Transition element contamination may be reduced to acceptable levels (i.e. one part in 1010) by glass refining techniques such as vapor-phase oxidation, which largely eliminates the effects of these metallic impurities.

However, another major extrinsic loss mechanism is caused by absorption due to water (as the hydroxyl or OH ion) dissolved in the glass. These hydroxyl groups are bonded into the glass structure and have fundamental stretching vibrations which occur at wavelengths between 2.7 and 4.2μm depending on group position in the glass network. The fundamental vibrations give rise to overtones appearing almost harmonically at 1.38, 0.95 and 0.72 μm, as illustrated in Figure 2.2. This shows the absorption spectrum for the hydroxyl group in silica.

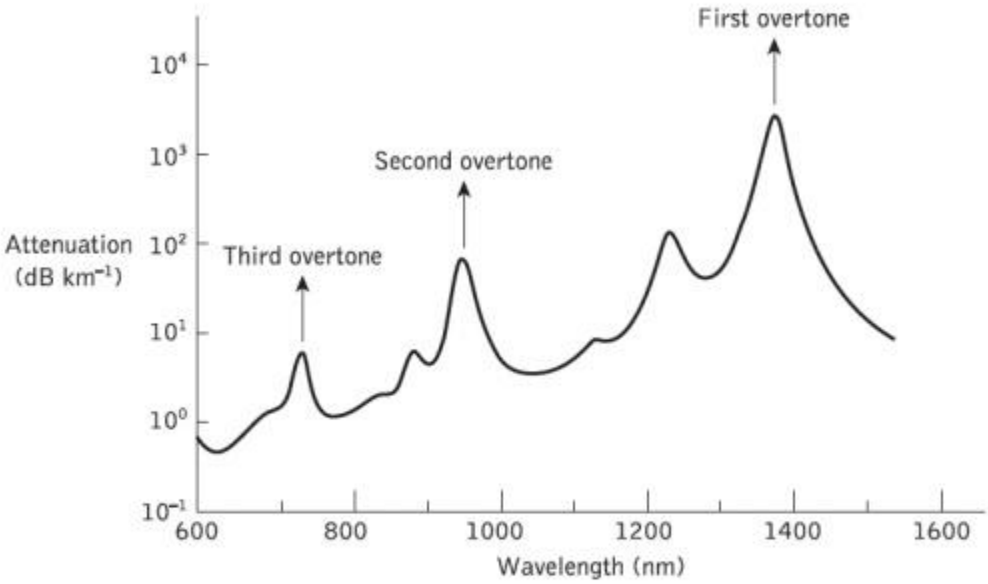

Figure 2.2 The absorption spectrum for the hydroxyl (OH) group in silica.

[Source: htpp://img.brainkart.com]

Furthermore, combinations between the overtones and the fundamental SiO2 vibration occur at 1.24, 1.13 and 0.88 μm, completing the absorption spectrum shown in Figure 2.2.It may also be observed in Figure 3.2 that the only significant absorption band in the region below a wavelength of 1 μm is the second overtone at 0.95 μm which causes attenuation of about 1 dB km−1 for one part per million (ppm) of hydroxyl.

At longer wavelengths the first overtone at 1.383 μm and its sideband at 1.24 μm are strong absorbers giving attenuation of about 2 dB km−1 ppm and 4 dB km−1 ppm respectively. Since most resonances are sharply peaked, narrow windows exist in the longer wavelength region around 1.31 and 1.55 μm which are essentially unaffected by OH absorption once the impurity level has been reduced below one part in 107.

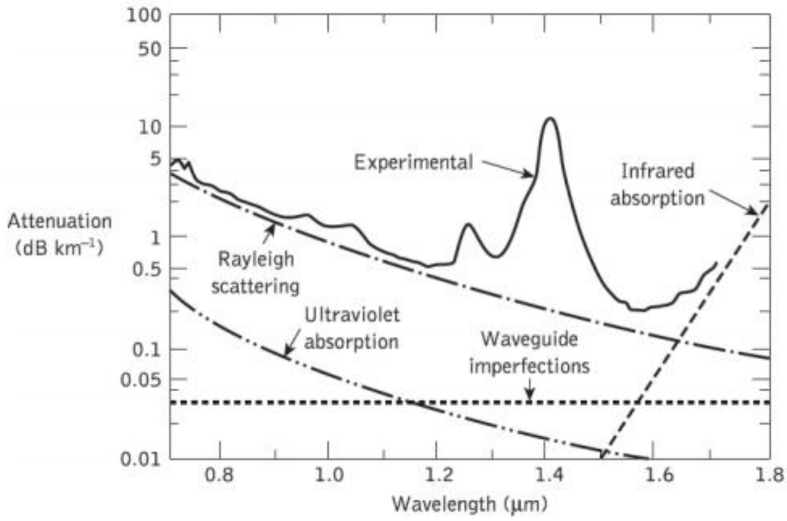

Figure 2.3 The measured attenuation spectrum for an ultra-low-loss single-mode fiber (solid line) with the calculated attenuation spectra for some of the loss mechanisms contributing to the overall fiber attenuation

[Source: htpp://img.brainkart.com]

This situation is illustrated in Figure 2.3, which shows the attenuation spectrum of a low-loss single-mode fiber produced in 1979. It may be observed that the lowest attenuation for this fiber occurs at a wavelength of 1.55 μm and is 0.2 dB km−1. Despite this value approaching the minimum possible attenuation of around 0.18 dB km−1 at the 1.55 μm wavelength, it should be noted that the transmission loss of an ultra-low-loss pure silica core fiber was more recently measured as 0.1484 dB km−1 at the slightly longer wavelength of 1.57μm. Although in standard, modern single-mode fibers the loss caused by the primary OH peak at 1.383 μm has been reduced below 1 dB km−1, it still limits operation over significant distances to the lower loss windows at 1.31 and 1.55 μm.

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 (proportionally to the mode power) into a different mode. This process tends to result in attenuation of the transmitted light as the transfer may be to 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.Linear scattering may be categorized into two major types: Rayleigh and Mie scattering. Both result from the nonideal physical properties of the manufactured fiber which are difficult and, in certain cases, impossible to eradicate at present.

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-in of density inhomogeneities are fundamental and cannot be avoided.

The subsequent scattering due to the density fluctuations, which is in almost all directions, produces an attenuation proportional to 1/λ4 following the Rayleigh scattering formula. For a single-component glass this is given by:

$$\gamma_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c K T_F \tag{2.4}$$

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 photoelastic coefficient, β_c is the isothermal compressibility at a fictive temperature T_F, and *K* is Boltzmann's constant. The fictive 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 following the relation:

$$\mathscr{L} = \exp(-\gamma_R L) \tag{2.5}$$

where L is the length of the fiber. It is apparent from Eq. (2.4) that the fundamental component of Rayleigh scattering is strongly reduced by operating at the longest possible wavelength.

2. Mie Scattering

Linear scattering may also occur at inhomogeneities which are comparable in size with the guided wavelength. These result from the nonperfect 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:

- ✓ removing imperfections due to the glass manufacturing process;
- ✓ carefully controlled extrusion and coating of the fiber;
- ✓ increasing the fiber guidance by increasing the relative refractive index difference.

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

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 significant 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

1. Stimulated Brillouin Scattering

Stimulated Brillouin scattering (SBS) may be regarded as the modulation of light through thermal molecular vibrations within the fiber. The scattered light appears as upper and lower sidebands which are separated from the incident light by the modulation frequency. The incident photon in this scattering process produces a phonon* of acoustic frequency as well as a scattered photon. This produces an optical frequency shift which varies with the scattering angle because the frequency of the sound wave varies with acoustic wavelength.

The frequency shift is a maximum in the backward direction, reducing to zero in the forward direction, making SBS a mainly backward process. As indicated previously, Brillouin scattering is only significant above a threshold power density. Assuming that the polarization state of the transmitted light is not maintained, it may be shown that the threshold power PB is given by:

$$P_B = 4.4 \times 10^{-3} d^2 \lambda^2 \alpha_{dB} \nu \text{ watts} \tag{2.6}$$

where d and λ are the fiber core diameter and the operating wavelength, respectively, both measured in micrometers, αdB is the fiber attenuation in decibels per kilometer and ν is the source bandwidth (i.e. injection laser) in gigahertz. The expression given in Eq. (2.6) allows the determination of the threshold optical power which must be launched into a single-mode optical fiber before SBS occurs.

2. Stimulated Raman Scattering

Stimulated Raman scattering (SRS) is similar to SBS except that a high-frequency optical phonon rather than an acoustic phonon is generated in the scattering process. Also, SRS can occur in both the forward and backward directions in an optical fiber, and may have an optical power threshold of up to three orders of magnitude higher than the Brillouin threshold in a particular fiber. Using the same criteria as those specified for the Brillouin scattering threshold given in Eq. (2.6), it may be shown that the threshold optical power for SRS PR in a long single-mode fiber is given by:

$$P_R = 5.9 \times 10^{-2} d^2 \lambda \alpha_{dB} \text{ watts} \tag{2.7}$$

Fiber Bend Loss

Optical fibers suffer radiation losses at bends or curves on their paths. This is due to the energy in the evanescent field at the bend exceeding the velocity of light in the cladding and hence the guidance mechanism is inhibited, which causes light energy to be radiated from the fiber. An illustration of this situation is shown in Figure 2.5. The part of the mode which is on the outside of the bend is required to travel faster than that on the inside so that a wavefront perpendicular to the direction of propagation is maintained.

Hence, part of the mode in the cladding needs to travel faster than the velocity of light in that medium. As this is not possible, the energy associated with this part of the mode is lost through radiation. The loss can generally be represented by a radiation attenuation coefficient which has the form:

$$\alpha_r = c_1 \exp(-c_2 R)$$

Where R is the radius of curvature of the fiber bend and $c1$, $c2$ are constants which are independent of R. Furthermore, large bending losses tend to occur in multimode fibers at a critical radius of curvature Rc which may be estimated from:

$$R_c \simeq \frac{3n_1^2\lambda}{4\pi(n_1^2 - n_2^2)^{\frac{3}{2}}} \quad (2.8)$$

It may be observed from the expression given in Eq. (2.8) that potential macrobending losses may be reduced by:

- ✓ designing fibers with large relative refractive index differences;
- ✓ operating at the shortest wavelength possible.

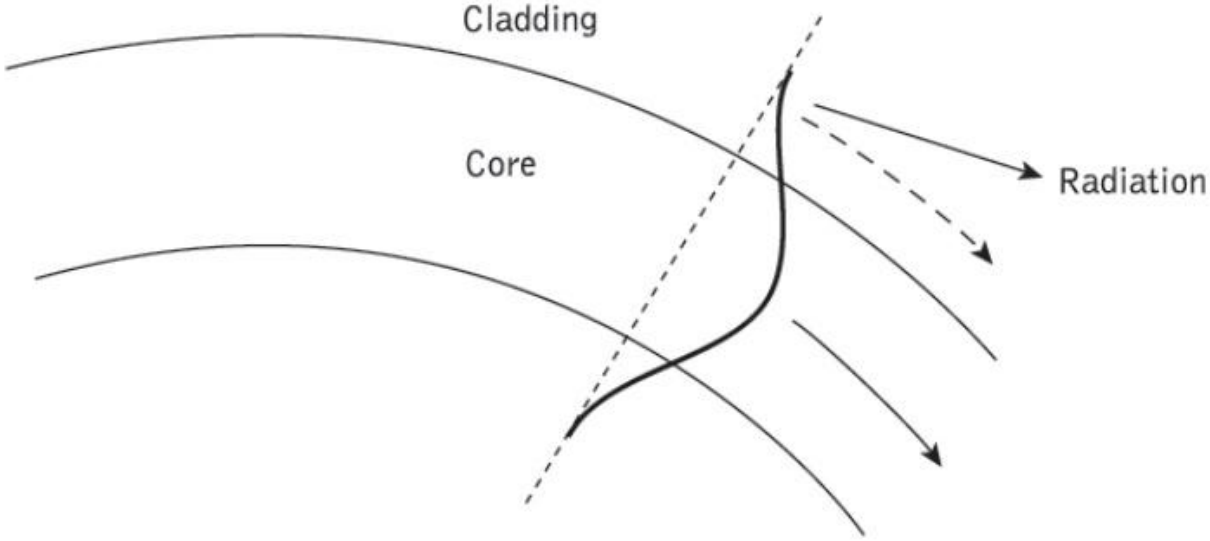

Figure 2.5 An illustration of the radiation loss at a fiber bend.

[Source: htpp://img.brainkart.com]

The above criteria for the reduction of bend losses also apply to single-mode fibers. One theory, based on the concept of a single quasi-guided mode, provides an expression from which the critical radius of curvature for a single-mode fiber *R*cs can be estimated as

$$R_{cs} \simeq \frac{20\lambda}{(n_1 - n_2)^{\frac{3}{2}}}\left(2.748 - 0.996\frac{\lambda}{\lambda_c}\right)^{-3} \qquad (2.9)$$

where λc is the cutoff wavelength for the single-mode fiber. Hence again, for a specific single-mode fiber (i.e. a fixed relative index difference and cutoff wavelength), the critical wavelength of the radiated light becomes progressively shorter as the bend radius is decreased.

Mid-Infrared and Far-Infrared Transmission

In the near-infrared region of the optical spectrum, fundamental silica fiber attenuation is dominated by Rayleigh scattering and multiphonon absorption from the infrared absorption edge (see Figure 2.2). Therefore, the total loss decreases as the operational transmission wavelength increases until a crossover point is reached around a wavelength of 1.55 μm where the total fiber loss again increases because at longer wavelengths the loss is dominated by the phonon absorption edge. Since the near fundamental attenuation limits for near-infrared silicate class fibers have been achieved, more recently researchers have turned their attention to the mid-infrared (2 to 5 μm) and the far-infrared (8 to 12 μm) optical wavelengths.

In order to obtain lower loss fibers it is necessary to produce glasses exhibiting longer infrared cutoff wavelengths. Potentially, much lower losses can be achieved if the transmission window of the material can be extended further into the infrared by utilizing constituent atoms of higher atomic mass and if it can be drawn into fiber exhibiting suitable strength and chemical durability. The reason for this possible loss reduction is due to Rayleigh scattering which displays a λ^{-4} dependence and hence becomes much reduced as the wavelength is increased. For example, the scattering loss is reduced by a factor of 16 when the optical wavelength is doubled.

Thus it may be possible to obtain losses of the order of 0.01 dB km^{-1} at a wavelength of 2.55 μm, with even lower losses at wavelengths of between 3 and 5 μm. Candidate glass-forming systems for mid-infrared transmission are fluoride, fluoride–chloride, chalcogenide and oxide.

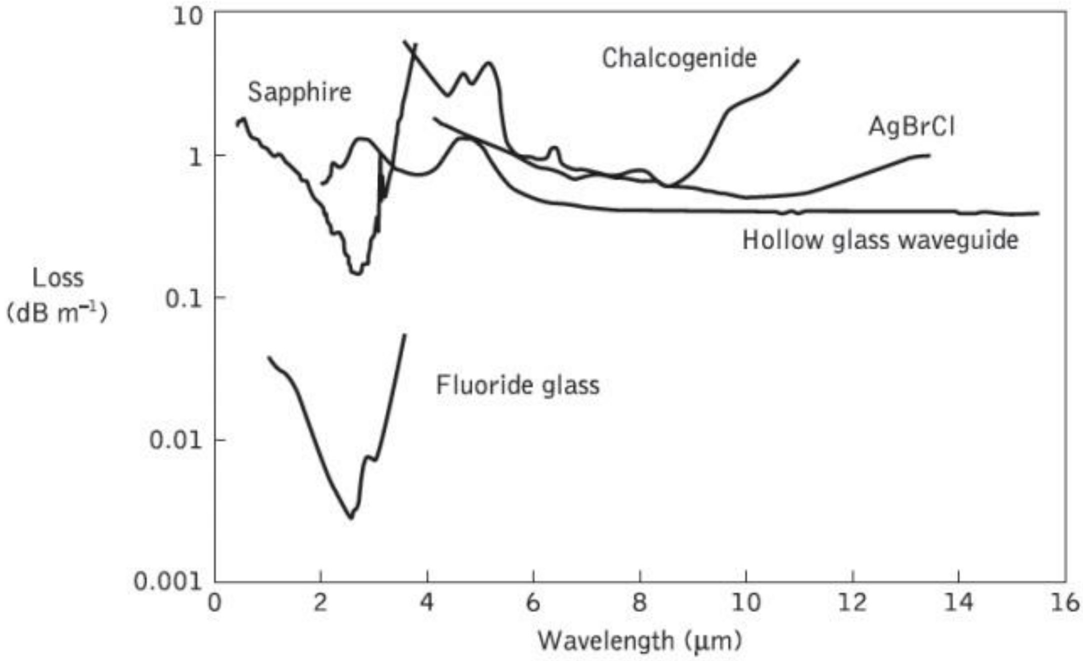

Figure 2.6 Attenuation spectra for some common mid- and far-infrared fibers

[Source: htpp://img.brainkart.com]

In particular, oxide glasses such as Al2O3 (i.e. sapphire) offer a near equivalent transmittance range to many of the fluoride glasses and have benefits of high melting points, chemical inertness, and the ability to be readily melted and grown in air. Chalcogenide glasses, which generally comprise one or more elements Ge, Si, As and Sb, are capable of optical transmission in both the mid-infrared and far-infrared regions.

A typical chalcogenide fiber glass is therefore arsenide trisulfide (As2S3). However, research activities into far-infrared transmission using chalcogenide glasses, halide glasses, polycrystalline halide fibers (e.g. silver and thallium) and hollow glass waveguides are primarily concerned with radiometry, infrared imaging, optical wireless, optical sensing and optical power transmission rather than telecommunications

The loss spectrum for a single-crystal sapphire fiber which also transmits in the midinfrared is also shown in Figure 2.6. Although they have robust physical properties, including a Young's modulus six times greater as well as a thermal expansion some ten times higher than that of silica, these fibers lend themselves to optical power delivery applications [Ref. 27], not specifically optical communications. Chalcogenide glasses which have their lowest losses over both the mid- and far-infrared ranges are very stable, durable and insensitive to moisture. Arsenic trisulfide fiber, being one of the simplest, has a spectral range from 0.7 to around 6 μm. Hence it has a cut off at long wavelength significantly before the chalcogenide fibers containing heavier elements such as Te, Ge and Se, an attenuation spectrum for the latter being incorporated in Figure 2.6. In general, chalcogenide glass fibers have proved to be useful in areas such as optical sensing, infrared imaging and for the production of fiber infrared lasers and amplifiers.