Photonics Technical Note # 21
Fiber Optics

Fiber Optics: Fiber Basics

Optical fibers are circular dielectric wave-guides that can transport optical energy and information. They have a central core surrounded by a concentric cladding with slightly lower (by ≈ 1%) refractive index. This difference in refractive indices allows the fiber to perform Total Internal Reflection inside the fiber and propagate light down its length.

Fibers are typically made of silica with index-modifying dopants such as GeO_2. A protective coating of one or two layers of cushioning material (such as acrylate) is used to reduce cross talk between adjacent fibers and the loss-increasing microbending that occurs when fibers are pressed against rough surfaces.

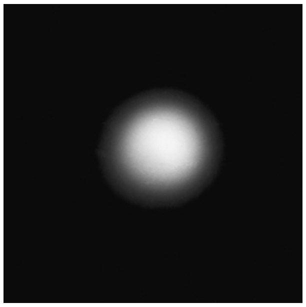
For greater environmental protection, fibers are commonly incorporated into cables. Typical cables have a polyethylene sheath that encases the fiber within a strength member such as steel or Kevlar strands.

The Fiber as a Dielectric Wave-Guide: Fiber Modes

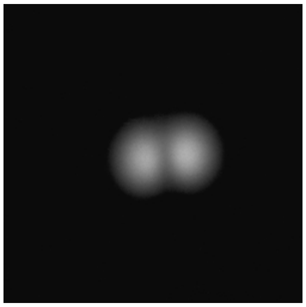
Since the core has a higher index of refraction than the cladding, light will be confined to the core if the angular condition for Total Internal Reflectance is met. The fiber geometry and composition determine the discrete set of electromagnetic fields, or fiber modes, which can propagate in the fiber.

There are two broad classifications of modes: radiation modes and guided modes. Radiation modes carry energy out of the core; the energy is quickly dissipated. Guided modes are confined to the core, and propagate energy along the fiber, transporting information and power. If the fiber core is large enough, it can support many simultaneous guided modes. Each guided mode has its own distinct velocity and can be further decomposed into orthogonal linearly polarized components. Any field distribution within the fiber can be expressed as a combination of the modes. The two lowest-order guided modes of a circularly symmetrical fiber — designated LP_{01} and LP_{11} — are illustrated in the Figure below.

When light is launched into a fiber, the modes are excited to varying degrees depending on the conditions of the launch — input cone angle, spot size, axial centration and the like. The distribution of energy among the modes evolves with distance as energy is exchanged between them. In particular, energy can be coupled from guided to radiation modes by perturbations such as microbending and twisting of the fiber — increasing the attenuation.



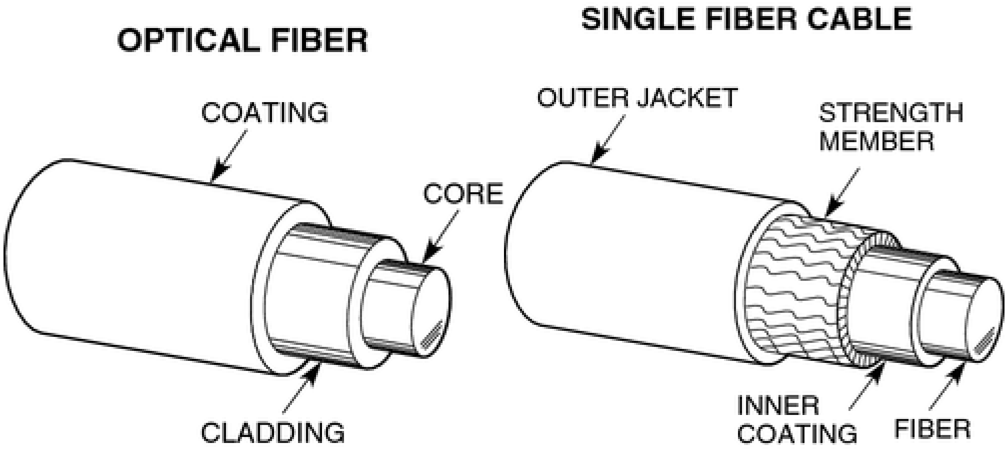
LP_{01} Mode Distribution



LP_{11} Mode Distribution

Physical Characteristics of Fiber

Optical fibers come in many different configurations. There are some characteristics that all fiber will demonstrate. For example, all optical fiber contain a core and a cladding. These two components make propagation of light with minimal loss possible. Other layers of a fiber optic cable are used for fiber protection and manufacturing purposes. In the figure below, layers of an optical fiber a depicted and labeled.



Cross section view of optical fiber and single fiber cable

Single Mode (SM) vs. Multi-Mode (MM) Fiber

There are a few factors that contribute to the type of mode propagation a fiber will demonstrate. These factors ultimately make up the fiber's V-number that determines which modes propagate in a fiber. These factors include: indices of refraction of core and cladding, core diameter, and wavelength. End users usually have constraints on the wavelength they want to use and the indices of refraction of core and cladding materials are typically fixed. Thus, the factor fiber manufacturers use to control the type of modes a fiber propagates is the core diameter.

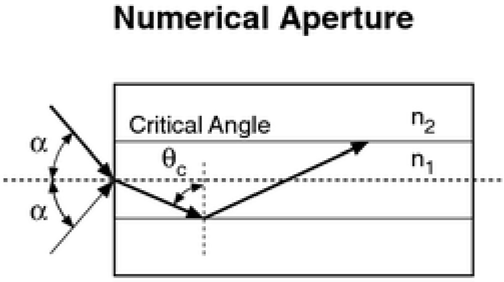
Single mode (SM) fibers have much smaller core diameters than Multi-Mode (MM) fibers. In the next section you will see mathematically how this directly lowers the fiber's V-number and the amount of modes that can propagate through the fiber. SM fiber is actually designed to propagate only a single (fundamental) mode from a light source. MM fiber allows higher order modes to propagate from a light source. Each SM fiber has a cut-off wavelength associated with it (this is also mathematically demonstrated in the next section). The cut-off wavelength is the benchmark where every lower wavelength will propagate high order modes and thus be considered multi-mode at those wavelengths. SM fiber is used to propagate LP_{01} Gaussian beam profiles. MM fiber is typically used when beam shape and quality is not a desirable factor. MM fiber is used to deliver as much light down the fiber as possible. MM fibers in turn have large NAs while SM mode fibers have smaller NAs.

Fiber Parameters

Numerical Aperture (NA)

The Numerical Aperture (NA) of a fiber is defined as the sine of the largest angle an incident ray can have for total internal reflectance in the core. Rays launched outside the angle specified by a fiber's NA will excite radiation modes of the fiber. A higher core index, with respect to the cladding, means larger NA. However, increasing NA causes higher scattering loss from greater concentrations of dopant. A fiber's NA can be determined by measuring the divergence angle of the light cone it emits when all its modes are excited.

Qualitatively, NA is a measure of the light gathering ability of a fiber. It also indicates how easy it is to couple light into a fiber.



NA = $\sin \alpha = \mathrm{sqrt}(n_1^2 - n_2^2) = \mathrm{sqrt}(n_{core}^2 - n_{clad}^2)$
Full Acceptance Angle = 2α

n_{core} (For SMF-28 fiber: n_{core} ~1.47 @ 1310nm)
n_{clad} (For SMF-28 fiber: n_{clad} ~1.46 @ 1310nm)

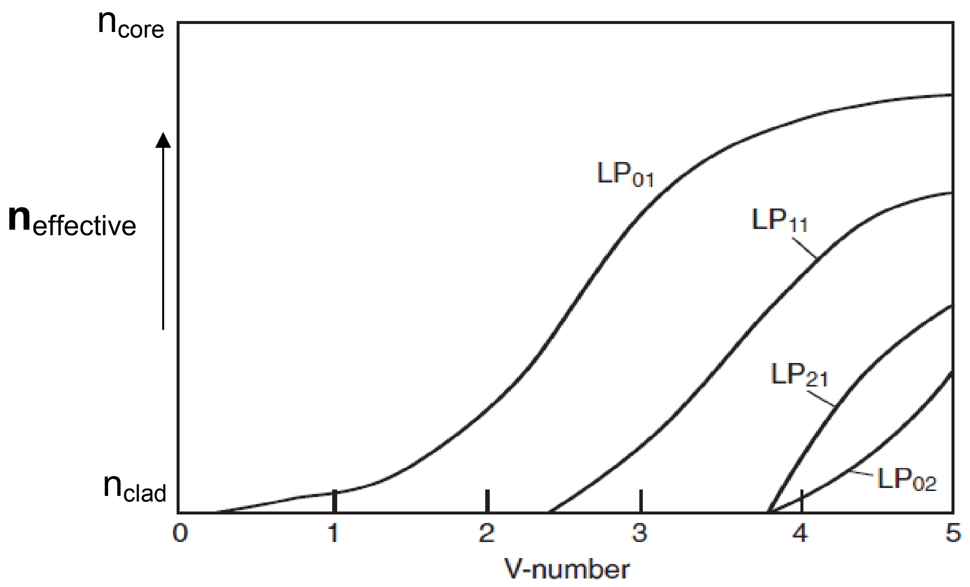
"V Number"

The Normalized Frequency Parameter of a fiber, also called the V number, is a useful specification. Many fiber parameters can be expressed in terms of V, such as: the number of modes at a given wavelength, mode cut off conditions, and propagation constants. For example, the number of guided modes in a step index multimode fiber is given by:

$V^2/2$, and a step index fiber becomes single-mode for a given wavelength when $V<2.405$. Mathematically:

$V = 2\pi \cdot NA \cdot a/\lambda = 2\pi \cdot a/\lambda \cdot \mathrm{sqrt}(n_{core}^2 - n_{clad}^2)$

a	is the fiber core radius
n_{core}	is the index of refraction of the core ($n_{core} > n_{clad}$)
n_{clad}	is the index of refraction of the cladding



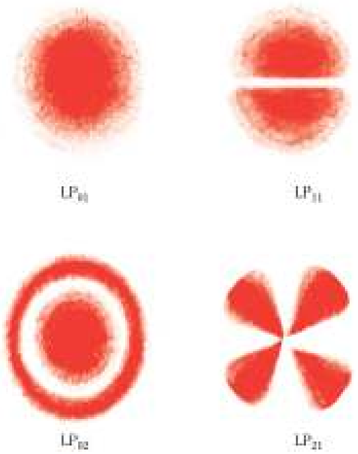
Dispersion curves for low order Linearly Polarized (LP) Modes of an Optical Fiber

Cutoff Wavelength

$\lambda_c = 2\pi \cdot a/V_c \cdot \mathrm{sqrt}\,(n_{core}^2 - n_{clad}^2)$

a	is the fiber core radius
n_{core}	is the index of refraction of the core
n_{clad}	is the index of refraction of the cladding
λ_c	is the cutoff wavelength
V_c	is the cutoff V number, equals 2.405

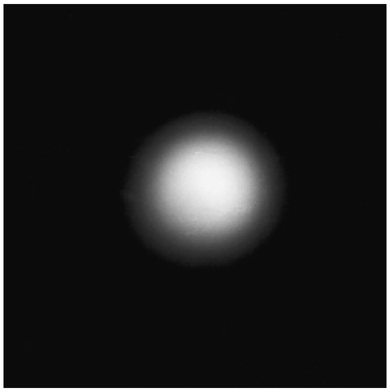
The cutoff wavelength is the minimum wavelength in which a particular fiber still acts as a single mode fiber. Above the cutoff wavelength, the fiber will only allow the LP_{01} mode to propagate through the fiber (fiber is a single mode fiber at this wavelength). Below the cutoff wavelength, higher order modes, i.e. LP_{11}, LP_{21}, LP_{02}, etc will be able to propagate (fiber becomes a multimode fiber at this wavelength).



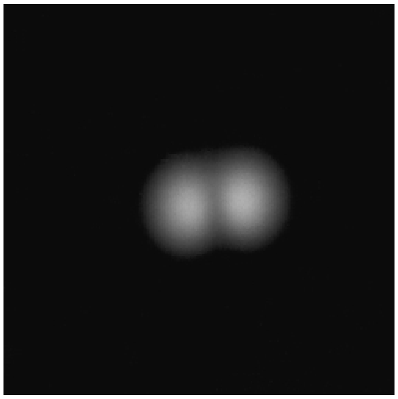
Irradiance patterns for low order LP Modes

Bandwidth Limitations

Bandwidth of an optical fiber determines the data rate. The mechanism that limits a fiber's bandwidth is known as dispersion. Dispersion is the spreading of the optical pulses as they travel down the fiber. The result is that pulses then begin to spread into one another and the symbols become indistinguishable. There are two main categories of dispersion, intermodal and intramodal.



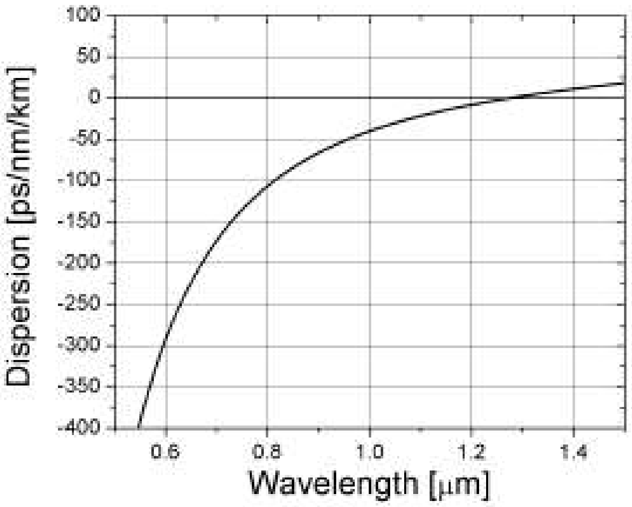
LP_{01} Mode Distribution



LP_{11} Mode Distribution

Intermodal Dispersion

As its name implies, intermodal dispersion is a phenomenon between different modes in an optical fiber. Therefore this category of dispersion only applies to mulitmode fiber. Since all the different propagating modes have different group velocities, the time it takes each mode to travel a fixed distance is also different. Therefore as an optical pulse travels down a multimode fiber, the pulses begin to spread, until they eventually spread into one another. This effect limits both the bandwidth of multimode fiber as well as the distance it can transport data.



Dispersion is expressed in units of ps/nm·km. Notice to minimize dispersion, operating around ~1.3um (zero dispersion wavelength) will significantly reduce dispersion.

Intramodal Dispersion

Intramodal Dispersion, sometimes called material dispersion, is a result of material properties of optical fiber and applies to both single-mode and multimode fibers. There are two distinct types of intramodal dispersion: **chromatic dispersion** and **polarization-mode dispersion**.

The index of refraction varies depending upon wavelength. Therefore, different wavelengths will travel down an optical fiber at different velocities. This is known as **Chromatic Dispersion**.

This principle implies that a pulse with a wider FWHM will spread more than a pulse with a narrower FWHM. Dispersion limits both the bandwidth and the distance that information can be supported. This is why for long communications links it is desirable to use a laser with a very narrow line width. Distributed Feedback (DFB) lasers are popular for communications because they have a single longitudinal mode with a very narrow line width.

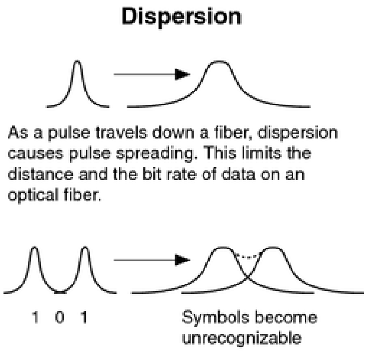
Polarization Mode Dispersion (PMD) is actually another form of material dispersion. Single-mode fiber supports a mode, which consists of two orthogonal polarization modes. Ideally, the core of an optical fiber is perfectly circular. However, the fact that in reality, the core is not perfectly circular, and mechanical stresses such as bending introduce birefringency in the fiber, causes one of the orthogonal polarization-modes to travel faster than the other, hence causing dispersion of the optical pulse.

Attenuation

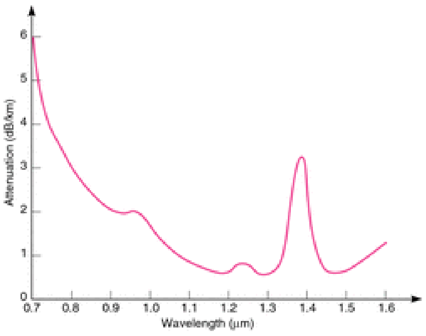
Light power propagating in a fiber decays exponentially with length due to absorption and scattering losses. Attenuation is the single most important factor determining the cost of fiber optic telecommunication systems, as it determines spacing of repeaters needed to maintain acceptable signal levels.

In the near infrared and visible regions, the small absorption losses of pure silica are due to tails of absorption bands in the far infrared and ultraviolet. Impurities — notably water in the form of hydroxyl ions — are much more dominant causes of absorption in commercial fibers. Recent improvements in fiber purity have reduced attenuation losses. State-of-the-art systems can have attenuation on the order of 0.1 dB/km.

Scattering can couple energy from guided to radiation modes, causing loss of energy from the fiber. There are unavoidable Rayleigh scattering losses from small-scale index fluctuations frozen into the fiber when it solidifies. This produces attenuation proportional to l/λ^4. Irregularities in core diameter and geometry or changes in fiber axis direction also cause scattering. Any process that imposes dimensional irregularities — such as microbending — increases scattering and hence attenuation.Typical Spectral



Dispersion



Typical Spectral Attenuation in Silica