Tutorial

Fiber Basics

Optical fibers are circular dielectric waveguides that can transport optical energy and information. They have a central core surrounded by a concentric cladding with slightly lower (by ≈ 1%) refractive index. 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 crosstalk 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 Waveguide: 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 which can propagate in the fiber. These fields are the fiber's modes.

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 symmetric fiber—designated LP$_{01}$ and LP$_{11}$—are illustrated at right.

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.

Bandwidth Limitations

Bandwidth of an optical fiber determines the amount of information that can be supported, in other words, 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.

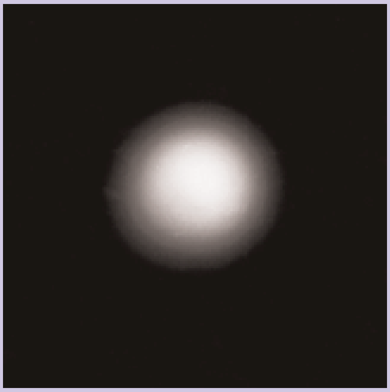
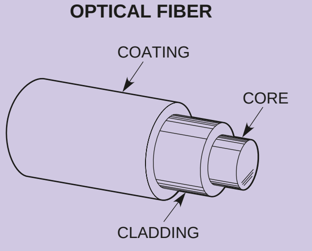
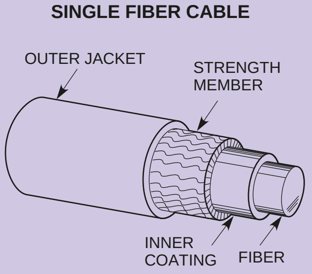


Figure 1a—LP$_{01}$ Mode Distribution

Figure 1b—LP$_{11}$ Mode Distribution

Figure 1—Dispersion





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.

Intramodal Dispersion

Intramodal dispersion, sometimes called material dispersion, is a category of dispersion that occurs within a single-mode. This dispersion mechanism 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.

Chromatic Dispersion. In silica, the index of refraction is dependent upon wavelength. Therefore different wavelengths will travel down an optical fiber at different velocities.

This implies that a pulse with a wider FWHM will spread more than a pulse with a narrower FWHM. This 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 linewidth. Distributed Feedback (DFB) lasers are popular for communications because they have a single longitudinal mode with a very narrow linewidth.

Polarization Mode Dispersion. Polarization Mode Dispersion (PMD) is actually another form of material dispersion. Single-mode fiber supports one mode, which consists of two orthogonal polarization modes. Ideally, the core of an optical fiber has an index of refraction that is uniform over the entire cross section, unless the fiber is graded index. However, mechanical stresses, i.e. bending, can cause slight changes in the index of refraction in one dimension. This can cause 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 Attenuation in Silica

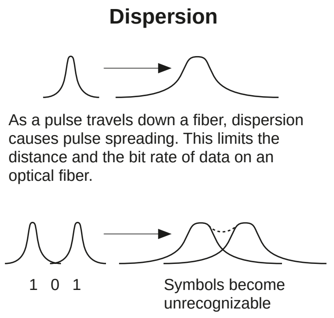


Figure 2—Dispersion

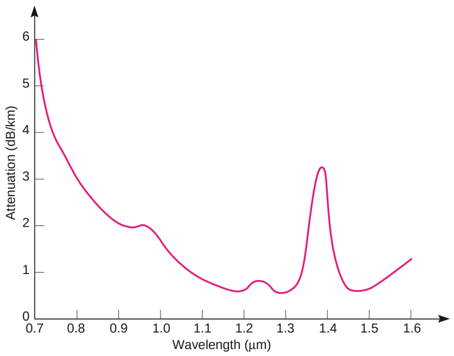


Figure 3—Typical Spectral Attenuation in Silica

Fiber Parameters

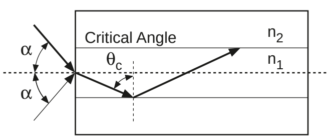
Numerical Aperture (NA)

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. The trade-offs involved in increasing NA include 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.

Numerical Aperture

Numerical Aperture



$NA = \sin\alpha = \sqrt{n_1^2 - n_2^2}$

Full Acceptance Angle = 2α

Figure 4—Numerical Aperture

"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, $V = 2\pi \cdot NA \cdot a/\lambda$ where "a" is the fiber core radius.

Fiber Preparation

Fiber Stripping

The outer sheath of fiber cables can be removed using electrical cable stripping tools, and the Kevlar strength member may be trimmed by scissors or a razor blade. However, the fiber coating must be very carefully removed to avoid damaging the fiber—surface flaws and scratches are the cause of most fiber failures. The coating can be removed using our F-STR fiber strippers.

Fiber Termination

End surface quality is one of the most important factors affecting fiber connector and splice losses. Quality endfaces can be obtained by polishing or by cleaving. Polishing is employed in connector terminations when the fiber is secured in a ferrule by epoxy. The following describes the popular connectors and their endface preparation styles.

Fiber Optic Connector Types

SMA—Due to its stainless steel structure and low-precision, threaded fiber locking mechanism, this connector is used mainly in applications requiring the coupling of high-power laser beams into large-core, multimode fibers. Typical applications include laser beam delivery systems in medical, bio-med, and industrial applications. The typical insertion loss of an SMA connector is greater than 1 dB.

ST—The ST connector is used extensively both in the field and indoor fiberoptic LAN applications. Its high-precision, ceramic ferrule allows its use with both multimode and single-mode fibers. The bayonet style, keyed coupling mechanism, featuring push and turn locking of the connector, prevents overtightening and damaging of the fiber end. The insertion loss of the ST connector is less than 0.5 dB, with typical values of 0.3 dB being routinely achieved. Drilled-out, metallic ST connectors, having insertion losses of >1 dB, are being used with Newport's large-core (>140 µm) fibers.

FC—The FC has become the connector of choice for single-mode fibers, and is mainly used in fiber-optic instruments, SM fiber optic components, and in high-speed fiber optic communication links. This high-precision, ceramic ferrule connector is equipped with an anti-rotation key, reducing fiber endface damage and rotational alignment sensitivity of the fiber. The key is also used for repeatable alignment of fibers in the optimal, minimal-loss position. Multimode versions of this connector are also available. The typical insertion loss of the FC connector is around 0.3 dB. Drilled-out, metallic FC connectors, having insertion losses of >1 dB, are being used with Newport's large-core (>140 µm) fibers.

SC—The SC connector is becoming increasingly popular in single-mode fiber optic telecom and analog CATV, field deployed links. The high-precision, ceramic ferrule construction is optimal for aligning single-mode optical fibers. The connectors' outer, square profile combined with its push-pull coupling mechanism, allow for greater connector packaging density in instruments and patch panels. The keyed outer body prevents rotational sensitivity and fiber endface damage. Multimode versions of this connector are also available. The typical insertion loss of the SC connector is around 0.3 dB.

A *detailed component list is also available for individual projects.*

Connector Endface Preparation

Once the optical fiber is terminated with a particular connector, the connector endface preparation will determine what the connector return loss, also known as back reflection, will be. The back reflection is the ratio between the light propagating through the connector in the forward direction and the light reflected back into the light source by the connector surface. Minimizing back reflection is of great importance in high-speed and analog fiber optic links, utilizing narrow linewidth sources such as DFB lasers, which are prone to mode hopping and fluctuations in their output.

Flat Polish—A flat polish of the connector surface will result in a back reflection of about -16 dB (4%).

PC Polish—The Physical Contact (PC) polish results in a slightly curved connector surface, forcing the fiber ends of mating connector pairs into physical contact with each other. This eliminates the fiber-to-air interface, there by resulting in back reflections of -30 to -40 dB. The /PC polish is the most popular connector endface preparation, used in most applications.

SPC Polish—In the Super PC (SPC) polish, an extended polishing cycle enhances the surface quality of the connector, resulting in back reflections of -40 to -55 dB. This polish is used in high-speed, digital fiber optic transmission systems.

APC Polish—The Angled PC (APC) polish, adds an 8 degree angle to the connector endface. Back reflections of <-60 dB can routinely be accomplished with this polish.

Fiber Cleaving is the fastest way to achieve a mirror-flat fiber end—it takes only seconds. The basic principle involves placing the fiber under tension, scribing with a diamond or carbide blade perpendicular to the axis, then pulling the fiber apart to produce a clean break. Our **F-BK2** or **FK11 Cleavers** make the process especially quick and easy. It is wise to inspect fiber ends after polishing or cleaving.

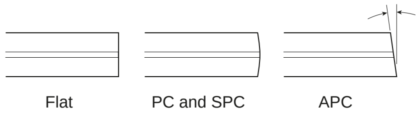


Figure 5—Connector Endfaces

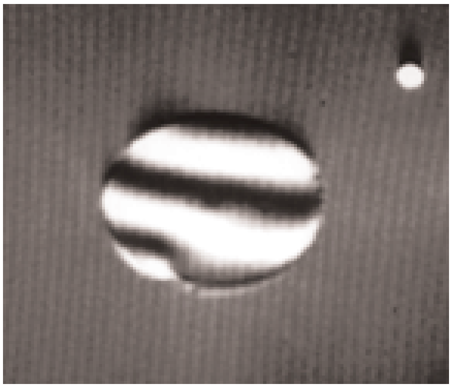


Figure 6—A typical F-BK2 cleave is clean, flat and perpendicular.

Coupling Light into Fibers

Good coupling efficiency requires precise positioning of the fiber to center the core in the focused laser beam. For multimode fibers, with their large cores, fiber positioners (e.g., Newport's **FP Series**) can achieve good coupling efficiency. Single-mode fibers require more elaborate couplers with submicron positioning resolution, like the **ULTRAlign** and **562F** stainless steel positioners and the **F-915** and **F-1015 Couplers**. These are also useful with multimode fibers when maximum coupling efficiency is required.

The characteristics of the focused beam must match the fiber parameters for good coupling efficiency. **For multimode fibers this is straight forward. General guidelines are**:

The focused spot should be comparable to the core size. The incident cone angle should not exceed the arcsine of the NA of the fiber (e.g. 23° for 0.2 NA and 35° for 0.3 NA).

To maximize coupling into a single-mode fiber, you must match the incident field distribution to that of the fiber mode. For example, the mode profile of the HE_{11} mode of a step index fiber can be approximated by a Gaussian distribution with a 1/e width w given by:

$$w = d\left(0.65 + \frac{1.619}{V^{1.5}} + \frac{2.879}{V^{6}}\right)$$

where: d is the core diameter

V is the “V-number.”

For our F-SV fiber, for which V = 2, the Gaussian width is approximately 28% larger than the core diameter, so the light should be focused to a spot size 1.28 times the core diameter at the fiber surface. For a Gaussian laser beam, the required beam diameter D incident upon focusing lens of focal length f to produce a focused spot of diameter w is $D = 4\lambda f/(\pi w)$. Given the laser beam waist and divergence, it's easy to determine the distance needed between the focusing lens and the laser to expand the beam to the required diameter.

The mode field diameter is now given to provide easier matching of lens to optical fiber for a Gaussian beam.

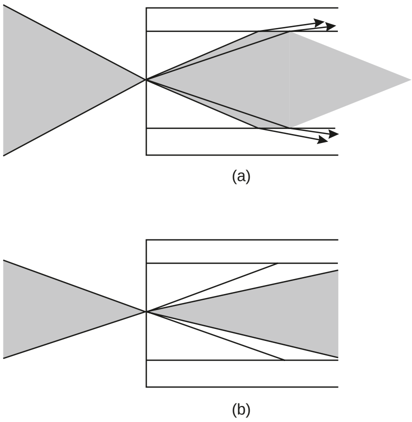
The diverging output beam of a laser diode must be collimated by a high numerical aperture lens before focusing. Newport's **F-L Series Diode Laser Focusing Lenses,** are AR-coated for high transmittance at popular laser diode wavelengths and—with numerical apertures up to 0.5—are useful for collimating or focusing.

Mode Scrambling and Filtering

Many multimode fiber experiments are sensitive to the distribution of power among the fiber's modes. This is determined by the launching optics, fiber perturbations, and the fiber's length. Mode scrambling is a technique that distributes the optical power in a fiber among all the guided modes. Mode filtering simulates the effects of kilometer lengths of fiber by attenuating higher-order fiber modes.

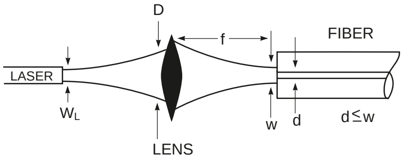
One scrambling technique is to splice a length of graded-index fiber between two pieces of step-index fiber—this ensures that the downstream fiber's core is overfilled regardless of launch conditions. Mode filtering can be achieved by wrapping a fiber several times around a finger-sized mandrel; bending sheds the high-order modes.

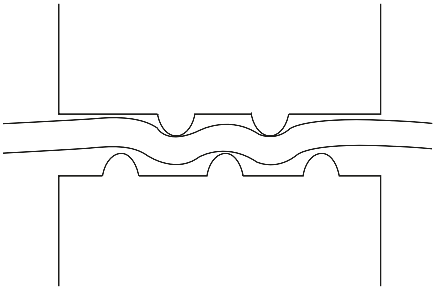
One way to achieve both scrambling and filtering is to introduce microbending to cause rapid coupling between all fiber modes and attenuation of high-order modes. One approach is to place a stripped section of fiber in a box filled with lead shot. A more precise way is to use Newport's **FM-1 Mode Scrambler**. This specially designed tool uses a calibrated mechanism to introduce microbending for mode scrambling and filtering.


(a)

(b)

Launching conditions in a multimode optical fiber. (a) Overfilled (b) Underfilled





Mode scrambler for optical fibers. The bends tend to couple out higher-order and radiation modes and to distribute the light into a distribution of modes that will remain stable over long distances.

Cladding Mode Removal

Some light is invariably launched into a fiber's cladding. Though cladding modes dissipate rapidly with fiber length, they can interfere with measurements. For example, the output of a single-mode fiber will not have a Gaussian distribution if light is propagating in the cladding. You can remove cladding modes by stripping a length of fiber coating and immersing the bare fiber in an index matching fluid such as glycerine.

Common Optical Parameters

The following is a list of common optical parameters associated with fiber optic components. Please call or visit Newport's website for application notes on how to measure these parameters.

Port Configuration: Number of input ports x number of output ports. e.g. 2 x 2

Coupling Ratio: The ratio of the power at an output port to the launched power expressed in dB. e.g. -10log (P2/P1).

Isolation: The ratio of the power at an output port in the transmitted wavelength band to that in the extinguished wavelength band, expressed in dB.

Directivity: The ratio of the power returned to any other input port to the launched power, expressed in dB. e.g.-10log (P4/P1).

Bandwidth: The range of operating wavelengths over which performance parameters are specified.

Excess Loss: The ratio of the total power at all output ports to the launched power, expressed in dB. e.g. -10log [(P2+P3)/P1].

Uniformity: The difference between maximum and minimum insertion losses.

Extinction Ratio: The ratio of the residual power in an extinguished polarization state to the transmitted power, expressed in dB.

Return Loss: The ratio of the power returned to the input port to the launched power, expressed in dB. e.g.-10log (P5/P1).

Polarization-Dependent Loss (PDL): The maximum (peak to peak) variation in insertion loss as the input polarization varies, expressed in dB.

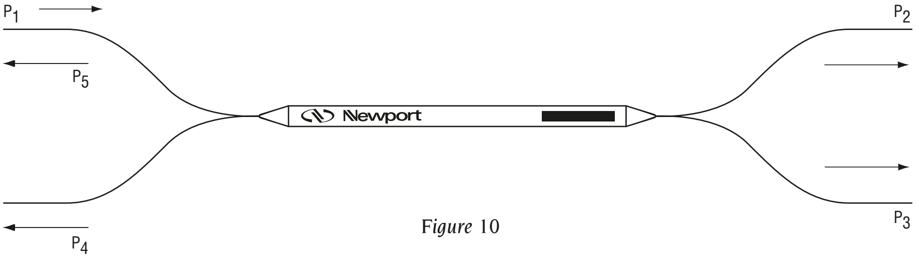


Figure 10