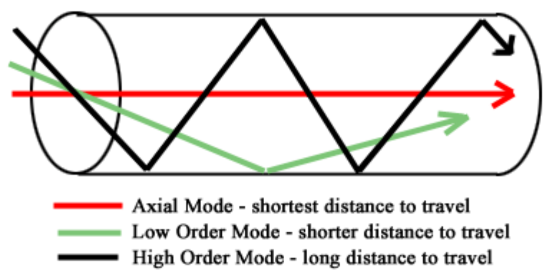
Photonics laboratory
Physics 472
Spring 2024

Experiment#8 Fiber Modes and Attenuation.

BACKGROUND

Fiber Modes

A Mode is a mathematical and physical concept describing the propagation of electromagnetic waves through media. In its mathematical form, mode theory derives from Maxwell's equations. We will deal with the solution to Maxwell's equations later. Now let us consider a mode as path in which light travels. A light signal can propagate through the core of the optical fiber on a single path (single-mode fiber) or on many paths (multimode fiber). The mode in which light travels depends on geometry, the index profile of the fiber, and the wavelength of the light.

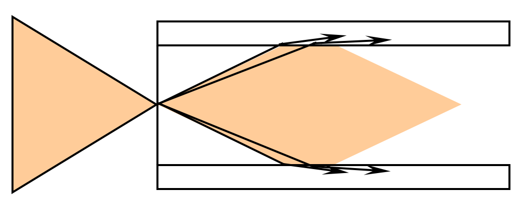


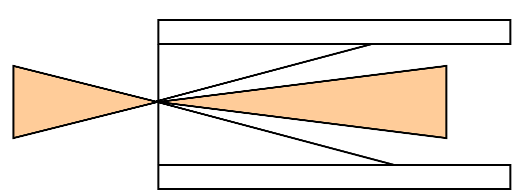
Modes in Multimode Fibers

The number of modes allowed in a given fiber is determined by a relationship between the wavelength (λ) of the light passing through the fiber, the core diameter of the fiber ($2a$), and the numerical aperture (NA) of the fiber. This relationship is known as the *Normalized Frequency Parameter*, or V number.

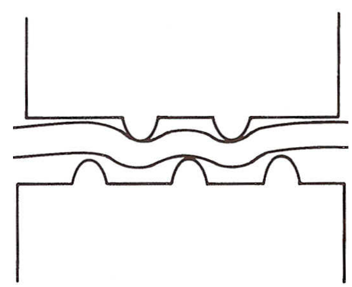
$$V = \frac{2\pi a NA}{\lambda}$$

The multimode fibers used for telecommunications may have a = 25 µm and NA = 0.20 or a = 50 µm and NA = 0.30, so that for 632.8 nm light, the V-number will be about 50 or 150, respectively. This means that a large number of modes will be supported by the fiber. The amount of light carried by each mode will be determined by the input, or launch, conditions. For example, if the angular spread of the rays from the source is greater than the angular spread that can be accepted by the fiber (the NA of the input radiation is greater than the NA of the fiber) and the radius of the


Overfilled


Underfilled

input beam is greater than the core radius of the fiber, then the fiber is said to be overfilled (see the figure). That is, some of the light which the source will be putting into the fiber cannot be propagated by the fiber. Conversely, when the input beam *NA* is less than the fiber *NA* and the input beam radius is less than that of the fiber, the fiber is underfilled (see the figure) and only low-order modes (low-angle rays in the ray picture) will be excited in the fiber. These two distributions will yield different measured attenuations, with the overfilled case having a higher loss than the underfilled case. In the ray picture, the higher-order rays will spend more of the time near the core-cladding interface and will have more of their evanescent field extending into the fiber cladding, resulting in higher attenuation. Also, if the fiber undergoes bending, the rays at high angles to the fiber axis may no longer satisfy the critical angle condition and not be totally internally reflected. Since power from these modes will radiate into the cladding and increase the attenuation, they are referred to as *radiation modes*. There is another class of modes called *leaky modes*. These modes have part of their electromagnetic energy distribution inside the core and part of their energy distribution in the cladding, but none of their energy distribution is actually at the core-cladding interface. The energy in the core "leaks" into the cladding by a process known, from quantum mechanics, *as tunneling*. Leaky modes are not true guided modes, but may not be fully attenuated until the light has traveled long distances. After light has been launched into a fiber and has propagated a considerable distance (which may be several kilometers), a distribution of power within the core of the fiber develops that is essentially independent of further propagation distance. This is called a stable mode distribution. To generate an approximation of a stable mode distribution that will not be sensitive to small bends and twists in the fiber orientation, even with only a short length of fiber, a technique called *mode filtering* is used. Mode filtering may be accomplished through the use of *mode scrambling*. Mode scrambling is done by bending the fiber in a series of corrugations, as shown in the figure. The effect of these bends is to couple out the light in the radiation and leaky modes and a portion of the light in the higher-order allowed modes and distribute the remaining light among the guided modes of the fiber, producing an approximation of the stable mode distribution. Mode scrambling permits repeatable, accurate measurements of fiber attenuation to be made in the laboratory, even with short lengths of fiber. It will be used in several of the projects in this course.



<u>*Losses in Fibers*</u>

In the above discussion, it has been assumed that the light travels down the fiber without any losses beyond those from radiation and leaky modes and some higher-order modes that are coupled out into the cladding.

When light is transmitted through an absorbing medium, the irradiance (energy per unit time per unit area) falls exponentially with the distance of transmission. This relation, called *Beer's Law*, can be expressed as

$$I(z) = I(0)e^{-\alpha z}$$

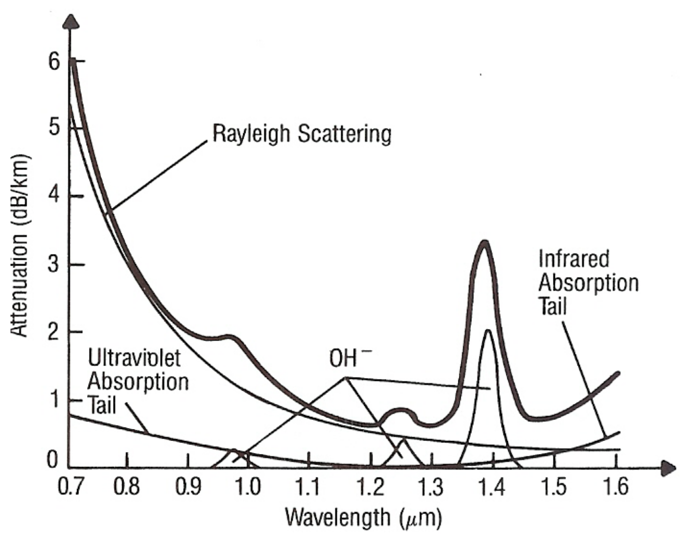
where $I(z)$ is the irradiance at a distance z from a point z = 0, and α is the attenuation coefficient, expressed in units reciprocal to the units of z. In some fields of physics and chemistry, where absorption by a material has been carefully measured, the amount of absorption at a particular wavelength for a specific path length, such as 1cm, can be used to measure the concentration of the absorbing material in a solution.

Although the absorption coefficient can be expressed in units of *reciprocal length* for exponential decay, in the field of fiber optics, as well as in most of the communications field, the *absorption is expressed in units of dB/km* (*dB* stand for decibels, tenths of a logarithmic unit). In this case, exponential decay is expressed using the base 10 instead of the base *e* (2.7182818...) as

$$I(z) = I(0)10^{-\frac{\alpha z}{10}}$$

where z is in kilometers and α is now expressed in decibels per kilometer (dB/km). Thus, a fiber of one kilometer length with an absorption coefficient of 10 dB/km permits $I(z)/I(0)$=0.10 or 10% of the input power to be transmitted through the fiber.

The losses in fibers are wavelength dependent. That is, light of different wavelengths introduced into the same fiber will suffer different amounts of loss. The figure shows the attenuation in dB/km of a typical optical fiber as a function of wavelength.



Although the exponential dependence was described for absorption losses, the same mathematics can be used for other sources of losses in fibers. Optical transmission losses in fibers are due to several mechanisms. First, optical fibers are limited in the short wavelength region (toward the visible and ultraviolet) by absorption bands of the material and by scattering from inhomogeneities in the refractive index of the fiber. These inhomogeneities are due to thermal fluctuations when the fiber is in the molten state. As the fiber solidifies, these fluctuations cause refractive index variations on a scale smaller than the parabolic variation that is imposed upon graded-index fibers. Scattering off of the inhomogeneities is known as Rayleigh scattering and is proportional to λ^{-4} where λ is the wavelength of the light. (This same phenomenon is responsible for the blue color of the sky. The stronger scattering of light at shorter wavelengths gives the sky its blue color.)

In the long wavelength region, infrared absorption bands of the material limit the long wavelength end of the radiation spectrum to about 1600 nm. These two mechanisms are the ultimate limit for fiber losses. The highest quality fibers are sometimes characterized by how closely they approach the Rayleigh scattering limit, which is about 0.17 dB/km at 1550 nm.

At one time metal ions were the major source of absorption by impurities in optical fibers. It was the elimination of these ions that produced low-loss optical fibers. Today, the only impurity of consequence in optical fibers is water in the form of the hydroxyl ion (OH^-), whose absorption bands at 950, 1250, and 1380 nm dominate the excess loss in today's fibers. They are evident in the absorption spectrum shown in the figure above.

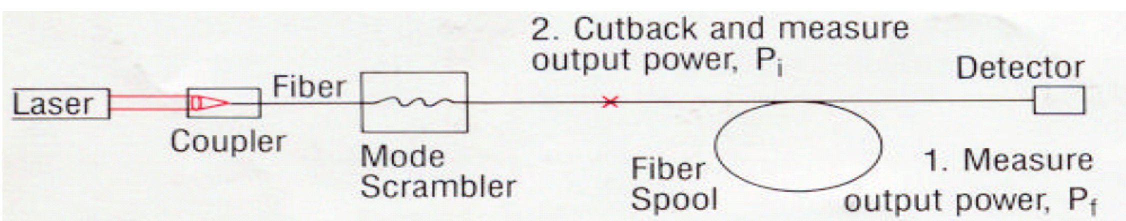
PROCEDURE

In this lab, you will measure one of the most important fiber parameters, the attenuation per unit length, of a multimode communications-grade optical fiber. The technique demonstrated here is called the "cutback method" and is generally used for this measurement.

You will also be introduced to the way that the conditions under which light is launched into the fiber can affect this measurement. You learn about mode scrambling and how to generate a desirable distribution of light in the fiber.

Measurement of Optical Fiber Attenuation

Because the designers of fiber optic systems need to know how much light will remain in a fiber after propagating a given distance, one of the most important specifications of an optical fiber is the fiber's attenuation. In principle, the fiber attenuation is the easiest of all fiber measurements to make. The method which is generally used is called the "cutback method." All that is required is to launch power from a source into a long length of fiber, measure the power at the far end of the fiber using a detector with a linear response, and then, after cutting off a length of the fiber, measure the power transmitted by the shorter length. The reason for leaving a short length of fiber at the input end of the system is to make sure that the loss that is measured is due solely to the loss of the fiber and not to loss which occurs when the light source is coupled to the fiber. The figure shows a schematic illustration of the measurement system.



In terms of the output power (P_f) before the cut and the output power after the cut (P_i) the transmission through the fiber is written as

$$T = \frac{P_f}{P_i}$$

If we substitute P_i and P_f for $I(0)$ and $I(z)$, respectively a logarithmic result for the loss (L) in decibels (dB), is then given by

$$L(dB) = -10\log\left(\frac{P_f}{P_i}\right)$$

The minus sign causes the loss to be expressed as a positive number. This allows losses to be summed and then subtracted from an initial power when it is also expressed logarithmically.

In working with fiber optics, you will often find powers expressed in dBm, which means "dB with respect to 1 mW of optical power." Thus, e.g., 0 dBm =1 mW, 3 dBm = 2 mW, and -10 dBm = 100 μW. Note that when losses in dB are subtracted from powers in dBm, the result is in dBm. For example, an initial power of + 3 dBm minus a loss of 3 dB results in a final power of 0 dBm. This is a shorthand way of saying "An initial power of 2 mW with a 50% loss results in a final power of 1 mW."

The attenuation coefficient, α, in dB/km is found by dividing the loss, L, by the length of the fiber, z. The attenuation coefficient is then given by

$$\alpha(dB/km) = -\frac{10}{z}\log\left(\frac{P_f}{P_i}\right)$$

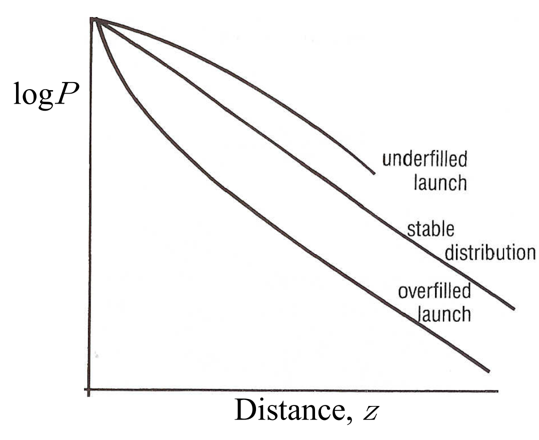
The total attenuation can then be found by multiplying the attenuation coefficient by the fiber length, giving a logarithmic result, in decibels (dB), for the fiber loss.

Practical Problems

The cutback method works well for high-loss fibers, with α on the order of 10 to 100 dB/km. However, meaningful measurements on low-loss fibers are more difficult. The highest-quality fibers will have losses which are on the order of 1 dB/km or less, so that cutting a full 1 km from the fiber will result in a transmitted power decrease of less than 20%, putting greater demands on the measurement system's resolution and accuracy.

There is also an uncertainty because the measured loss will depend on the characteristics of the way in which light is launched into the fiber. The launch conditions which result in an overfilled or underfilled fiber were discussed above. When a fiber is overfilled, many high-order and radiation modes are launched. These modes are more highly attenuated than are low-order modes. When a fiber is underfilled, mostly low-order modes are launched, and lower losses occur.

The solution to this problem is to attempt to generate what is known as the stable mode distribution as quickly as possible after launching. The near figure compares the transmission characteristics of the stable distribution with those of the overfilled and underfilled launch conditions. *The stable mode distribution may be achieved, even in a short length of fiber, by using* ***mode scrambling*** *to induce coupling between the modes shortly after the light is launched.*



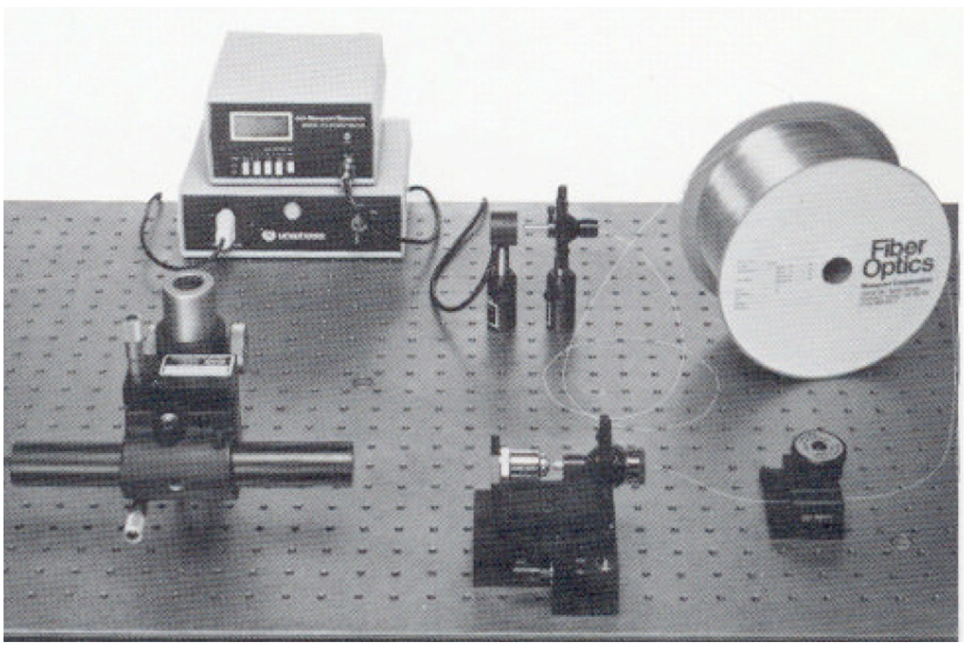
Mode scrambling generates an approximation of a stable distribution immediately after launch and allows repeatable measurements, which approximate those that would be found in the field, to be made in the laboratory. The above figure compares the optical power in a fiber as a function of propagation distance for the three types of launch conditions: overfilled, underfilled, and stable distribution. *The slope of the curve at large distances is equal to the attenuation coefficient.* It is the fact that the mode scrambling generates a stable distribution immediately after the source that allows a short cutback length to be used in the cutback method of measuring attenuation.

EXPERMENTS

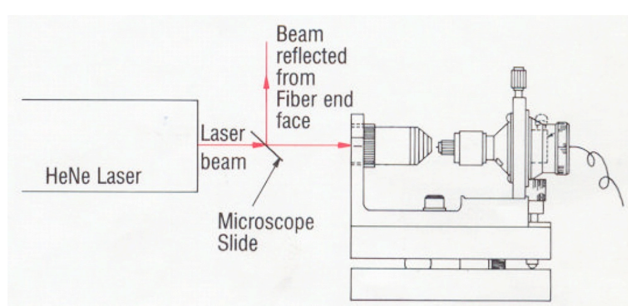
Task#1: Measurement of Optical Fiber Attenuation

1. Prepare both ends of the 500 meter fiber spool as you learned to do in lab#1. This fiber has a 100 μm core and a 140 μm outside diameter (OD). You may have to use some care in freeing the end of the fiber which was the start of the winding onto the spool. (this end will be referred to as the far end of the fiber.)

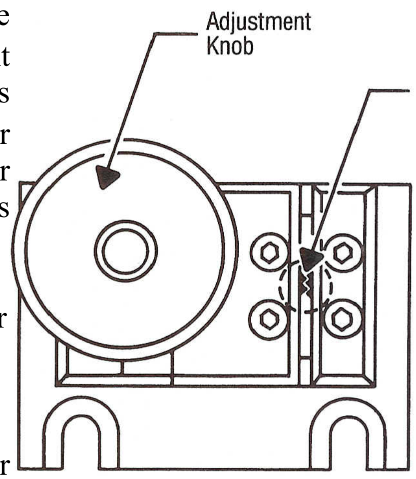
2. Place the cleaved far end of the fiber in a Fiber Chuck and insert this into the post-mounted Fiber Positioner. Also, post mount the detector head of the power meter. Align the detector head with the fiber end so that you will be able to measure the output power. The laboratory set-up for this project is shown in the picture below.



3. The use of the Fiber Coupler to couple light from a HeNe laser into a fiber is illustrated in the figure to the right. Align the coupler and the HeNe laser so that the laser beam shines along the axis of the Fiber Coupler. Mount a 20X microscope objective in the Fiber Coupler. Place the cleaved front end of the fiber into the fiber chuck from the Fiber Coupler and insert this into the coupler. Carefully align the fiber to maximize the light launched into the fiber, using the power meter to monitor the launched power. Use a microscope slide cover glass in the path of the laser beam to look at the



Fresnel reflection from the fiber end face. Focus the Fresnel reflected beam by adjusting the z component of the fiber position, as defined in the figure. This is done by turning the z adjustment knob on the fiber positioner. When this reflection is focused, the fiber end face is in the focal plane of the coupler's microscope objective lens.



4. Position the Mode Scrambler at a convenient place near the launch end of the fiber, as shown in the picture of the experimental setup above.

5. Rotate the knob of the Mode Scrambler counterclockwise to fully separate the two corrugated surfaces. The Mode Scrambler is illustrated below. Place the fiber between the two corrugated surfaces of the Mode Scrambler. Leave the fiber jacket on to protect the fragile glass fiber. Rotate the knob clockwise until the corrugated surfaces just contact the fiber. Examine the far-field distribution of the output of the fiber. Rotate the knob further clockwise and notice the changes in the distribution as the amount of bending of the fiber is changed. Since a narrow, collimated HeNe beam is being used to launch light into the fiber, the original launched distribution will be underfilled. When the distribution of the output just fills the *NA* of the fiber, an approximation of the stable distribution has been achieved. Do not add any more bending than is necessary to accomplish this, since that will result in excess loss. This launching and mode scrambling set-up should not be changed again during the remainder of the experiment.

6. Measure the power out of the far end of the fiber. Note the exact length of the fiber. It will be part of the information on the label of the spool.

7. Break off the fiber 1/2 meter after the mode scrambler from the launching set-up. Be sure to note on the spool how much fiber you have removed, so that other people using the same spool in the future will be able to obtain accurate results. Cleave the broken end of the fiber and measure the output from the cutback segment.

8. Calculate the fiber attenuation, using the equation given above, and compare this with the attenuation written in the fiber specification on the spool. Your value is probably somewhat higher than the specification. Why?