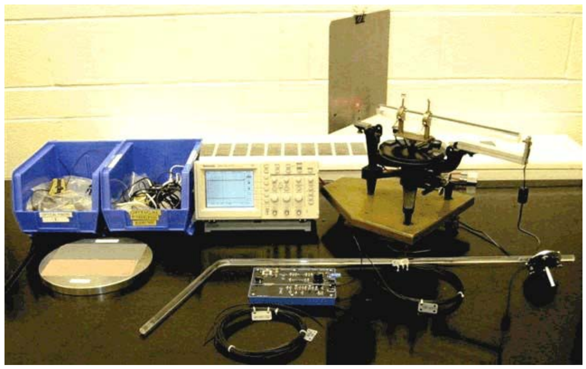
OPTICAL FIBERS

References:
J. Hecht: *Understanding Fiber Optics,* Ch. 1-3, Prentice Hall N.J. 1999
D.R. Goff: *Fiber Optic Reference Guide* (2^{nd} ed.) Focal Press 1999
Projects in Fiber Optics (Applications Handbook) Newport Corporation 1986 (copy available at the Resource Center)



INTRODUCTION

Optical fibers offer a faster, clearer and most efficient method of transmission of information than copper wires. In the field of medicine, the ability to insert optical fibers inside small hollow tubes that are pushed through small incisions in the body has provided a number of successful surgical procedures that do not call for massive cut of tissues. In the first part of this experiment you will learn how to investigate some of the physical properties of a transparent object, such as: index of refraction and total internal reflection. You will then study the speed of light propagation in optical fibers of different lengths, as well as the attenuation of light in the fiber material.

REFRACTION OF LIGHT

If light passes from a medium with a lower index of refraction n_1 to one with a higher index n_2, the light is bent toward the normal. If the light passes from n_2 to n_1 it is bent away from the normal. *Snell's Law* determines the amount of this bending, and for the passage from air to glass it is expressed as:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{1}$$

where θ_1 is called angle of incidence and θ_2, is the angle of refraction.

2. Total internal reflection

Snell's Law indicates that refraction cannot take place when the angle of incidence is too large. Figure 1 presents three light rays in a glass block. Light cannot get out of the glass if the angle of incidence exceeds a value called *the critical angle,* where the sine of the angle of refraction would equal 1.0 (ray 2-2'). Instead, *total internal reflection* bounces the light back into the glass, obeying the law of reflection (ray 3-3').

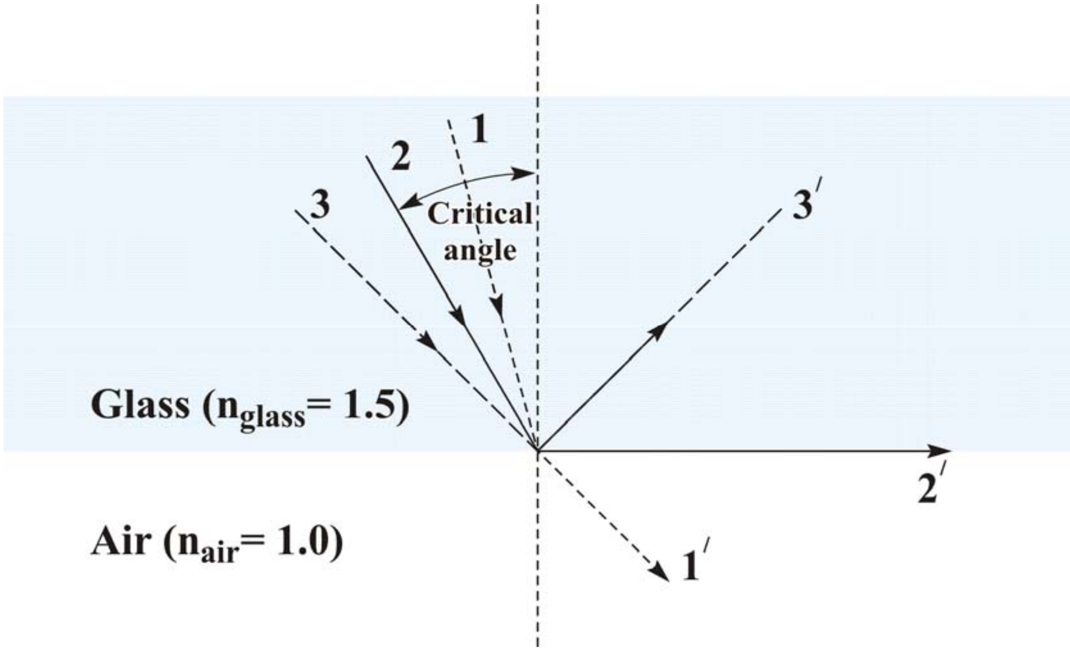


Figure 1
Ray 1-1': Light is refracted when passes from glass to air.
Ray 2-2': The angle of incidence equals the critical angle**;** light will travel tangent to the surface of separation.
Ray 3-3': The angle of incidence exceeds the critical angle; light will be reflected back in glass (total internal reflection).

The **critical angle** (θ_c) can he deduced from Snell's Law:

$$\theta_c = \sin^{-1}\left(\frac{n_{air}}{n_{glass}}\right) \tag{9}$$

When light tries to emerge from glass (n_{glass} = 1.5) into air (n_{air} = 1.0), the critical angle is 41.8°.

3. Optical fibers

Optical fibers are extremely thin strands of glass or other materials designed to transmit light signals from a transmitter to a receiver. These signals can be combinations of video, audio or data information. Optical fibers are lighter, cheaper and provide a better signal quality and a broader bandwidth than any other cable alternative. They are immune from electromagnetic radiation and lightning and they can carry the same signals with similar or superior signal quality for *50* miles or more without needing intermediate amplification.

Structure and properties of optical fibers

Most fibers are made of very pure glass (silica or silicon dioxide), with very small levels of impurities to adjust the refractive index. Special-purpose fibers are made of materials in a glassy state, but different from silica. For example, fibers for infrared applications are fluoride compounds.
Optical fibers are generally strong, stiff, yet flexible.

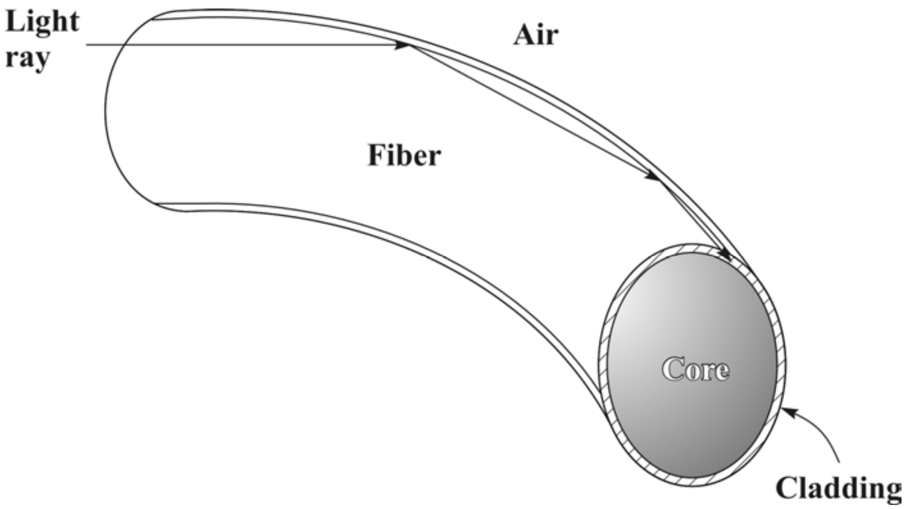


Figure 2. Confining of light in an optical fiber

All fibers share the same fundamental structure. The center of the fiber is the *core* - the region that carries the light. It has a higher refractive index than the surrounding *cladding.* The role of the cladding is to keep the light from leaking out (see Figure *2).*

Light guiding in optical fibers. The cladding completely surrounds the core of an optical fiber. The refractive index of the core is usually higher by only 1% than that of the cladding, so the critical angle is about 82°. Light is confined in the core if it strikes the interface with the cladding at an angle of 8° or less to the surface. The upper limit (8°) is called *confinement angle.*.

Getting light into an optical fiber is crucial for experimental purposes or technological applications. Light confinement in a fiber is measured by the angle over which light rays entering the fiber will be guided along its core (Figure 3).

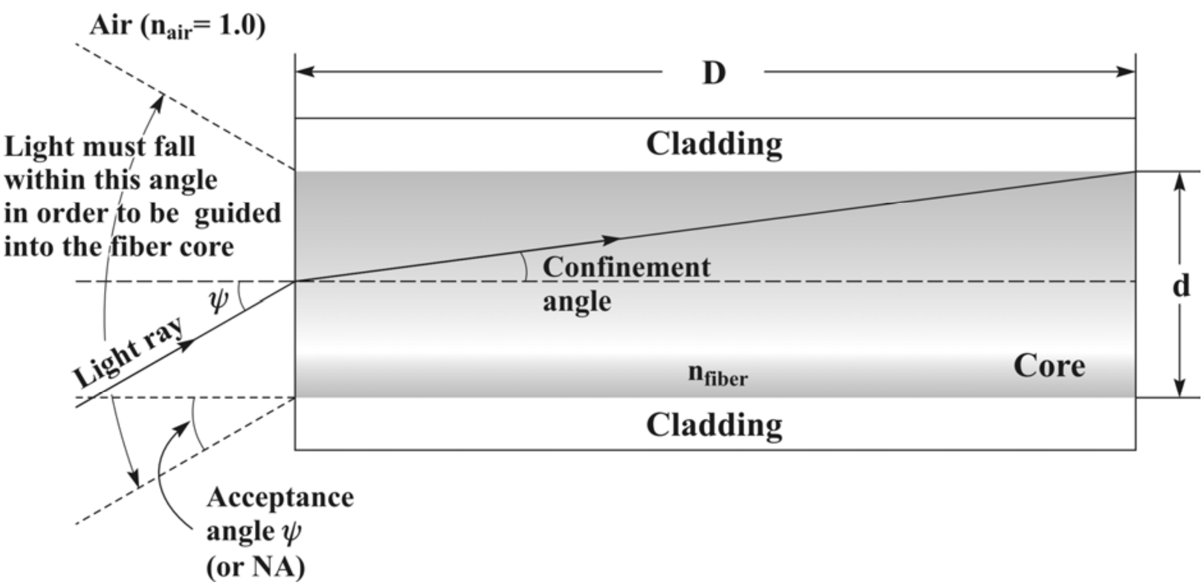


Figure 3. Acceptance and confinement angles in an optical fiber

The acceptance angle is measured outside the fiber; it differs from the confinement angle in the core material. Light must fall inside this angle to be guided in the fiber.

The acceptance angle is measured as numerical aperture (NA) which for light entering a fiber from air is approximately:

$$NA = \sqrt{n_0^2 - n_1^2} \qquad (10)$$

where n_0 is the refractive index of the core and n_1 is the index of the cladding. For a fiber with core index of 1.50 and cladding index of 1.485 (a 1% difference), NA = 0.21.

Transmission and attenuation
Transmission of light by optical fibers is not 100% efficient. Some light is lost causing attenuation of the signal. Among the mechanisms involved there are: scattering of light out of the fiber core, leakage of light caused by environmental factors, absorption by impurities within the fiber. The degree of attenuation also depends on the wavelength of light transmitted by the fiber.

Measurements of attenuation are made in decibels (dB): logarithmic units measuring the ratio of output to input power.
Loss (attenuation) in decibels is defined, as:

$$L(dB) = -10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \qquad (11)$$

P_{in} and P_{out} are: power into the fiber and power out of it.
Optical fibers have a **characteristic attenuation** (attenuation coefficient Γ) that is measured in decibels per unit length, normally decibels per kilometer

$$\Gamma(dB/km) = \frac{-10}{z}\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \qquad (12)$$

(12)

where z is the fiber length.

For example: in a fiber with 10dB/km attenuation, only 10% of the light that enters the fiber emerges after 1-km length

Experiment
1. Total internal reflection in an acrylic rod (qualitative)
A long transparent acrylic rod is a good experimental model for an optical fiber. You'll use a light source (laser diode), an acrylic rod, a turning table placed on a divided circle and a screen. Use the special attachment for the rod and place it on the rotating table. Arrange the rod with one end perpendicular to the laser beam (you'll see the light reflected back on the laser head). With the table locked, by rotating the laser arm, you may vary the incidence angle. The distance between the rod end and the laser should be 10-20 cm.
1.1 The "light pipe" (qualitative observation)
Place the end of the long acrylic rod at a small incidence angle of the laser light. Rotate it slowly until you form the "light pipe". Observe the light paths and explain how the light is kept inside the rod. Why are there a number of very bright points on the rod surface? Why is the light diffuse toward the rod end?
Hint: take the measurements in a dark room, view the rod from above.

2. The Optical Fiber

2.1 The oscilloscope

The digital real—time storage instrument that you will use is a complex one. While doing your experiment, you will be using a number of the main oscilloscope functions, so it may be useful if you will consult the Tektronix reference: www.tek.com/Measurement/App_Notes/XYZs/ before coming to the lab. If you have never used an oscilloscope, you may also watch a 15 minutes video tape "How do you use an oscilloscope" available from the Resource Center.

The oscilloscope controls can be divided into three groups:

- Controls for the vertical (y) motion of the beam: vertical position, vertical sensitivity. CH 1 ↔ CH 2 beam selection **DC**-**AC**-**G**round input coupling switches;
- Controls for the horizontal (x) motion of the beam: horizontal sweep speed, horizontal position, x sensitivity (when the oscilloscope is in the x-y mode)
- Controls of the time base circuits, which internally feed the x deflection of the beam (trigger control).

Each of the main buttons calls up a menu on the right of the screen and the buttons beside the menu allow you to select various functions.

The oscilloscope measures the voltage between the central wire of the coaxial input cable and the grounded outer wire braid. You will be using two inputs (CH 1 and CH 2) of the oscilloscope and will have two traces on the screen.

2.2 Optical fiber preparation

Efficient transmission of light by an optical fiber depends on the coupling between the light source and the fiber as well as between the fiber and the optical detector used to measure the fiber output. Therefore, special attention is paid to cutting and polishing the ends of a fiber cable.

Complete Steps 1 through 3 below for both ends of a 30cm fiber:

1. Cut 1 to 2 mm off the end of the fiber with the blade, using the alignment kit.
2. Use the polishing paper Polish the end of the fiber by moving it in an "eight" pattern.

Keep the fiber perpendicular to the polishing surface. Examine the end of the fiber by using a magnifying glass. If the end is cloudy or has scratches, repeat Step 2.

3. Remove 2 to 3 mm of jacket with a wire stripper to expose bare fiber. Avoid nicking the fiber.

2.3 Equipment Set-Up and Calibration

Oscilloscope settings: VOLTS/DIV of each channel are displayed at the bottom (left) of the screen. The TRIGGER source and level (in mV) are displayed at the bottom (right) of the display.

CH1 menu: Coupling=AC; BW Limit=ON (20 MHz). VOLTS/DIV=(Start at 0.2V, decrease if needed).

CH2 menu: Coupling=AC; BW Limit=ON (20 MHz), VOLTS/DIV=(Start at 0.1 V, decrease if needed). Set CH1 as OFF.

TRIGGER menu: Source=CH1, Mode=Auto, Coupling=AC, LEVEL=make it positive

HORIZONTAL: SEC/DIV=50 ns

Connections. Set-up the following:

- Hook probe of CH1 to "Reference" on the apparatus; ground lead of CH1 probe to Ground test point below "Reference".
- Hook probe of CH2 to "Delay"; ground lead of CH2 probe to Ground test point below "Delay".
- "Calibration Delay" knob to the midway position.

Select the 0.3 m fiber prepared as outlined before. Insert one of its ends into D3 (LED – light emitting diode) until seated, then tighten it with the locking nut. The other end has to be inserted and tightened into Detector D8.
The pulse observed on CH1 is the calibration pulse. Note its amplitude and pulse width (at half of the maximum amplitude).
The 0.3m fiber will simulate a distance of zero (the time delay is less than 1 ns). With CH2 turned to ON, the pulse received from the 0.3 m fiber optic cable will be visible. Using the vertical position knobs, align the bases of CH1 and CH2 traces with one of the horizontal grid lines. Rotate the "Calibration Delay" knob until the peak of the received pulse coincides with the peak of the reference pulse. Measure the amplitude A_0 (mV) of the received pulse. P_{in} from Equations (11) and (12) is proportional to A_0^2.

2.4 Attenuation

Without changing the calibration settings, connect the 5 m fiber. *Note: The fiber should be deeply inserted and well tightened with the locking nut.* Check how the amplitude changes if you bend the fiber. Measure the received pulse amplitudes A_i (mV) for different fiber lengths (5m – 30m). P_{out} from (11 – 12) is proportional to A_i^2. Does it matter that the fibers are looped? Determine the attenuation coefficient of the fiber material from the semi-logarithmic plot of (12). How much (in %) of an original signal will emerge from a 10km fiber of the same material?

2.5 Speed of light in the optical fiber

Use the CURSOR function of the oscilloscope to measure the delay time, Δt of the received pulse from each fiber (how much, in units of time, the fiber pulse is displaced with respect to the calibration pulse). From an appropriate plot (fiber length L vs. Δt), determine the speed of light propagation in the optical fiber material (v), knowing the refraction index: $n_{fiber} = 1.492$ and assuming speed of light in vacuum $c = 3 \times 10^8$ m/s. Comment the result; analyze the sources of error.

Hint: use $$v = \frac{L}{\Delta t} \quad \text{and} \quad \frac{c}{n_{fiber}} = v$$

This guide sheet was written by R.M. Serbanescu in 2000, reviewed in 2002 and 2004. Thanks to Mr. Takashi Sato for valuable advice.