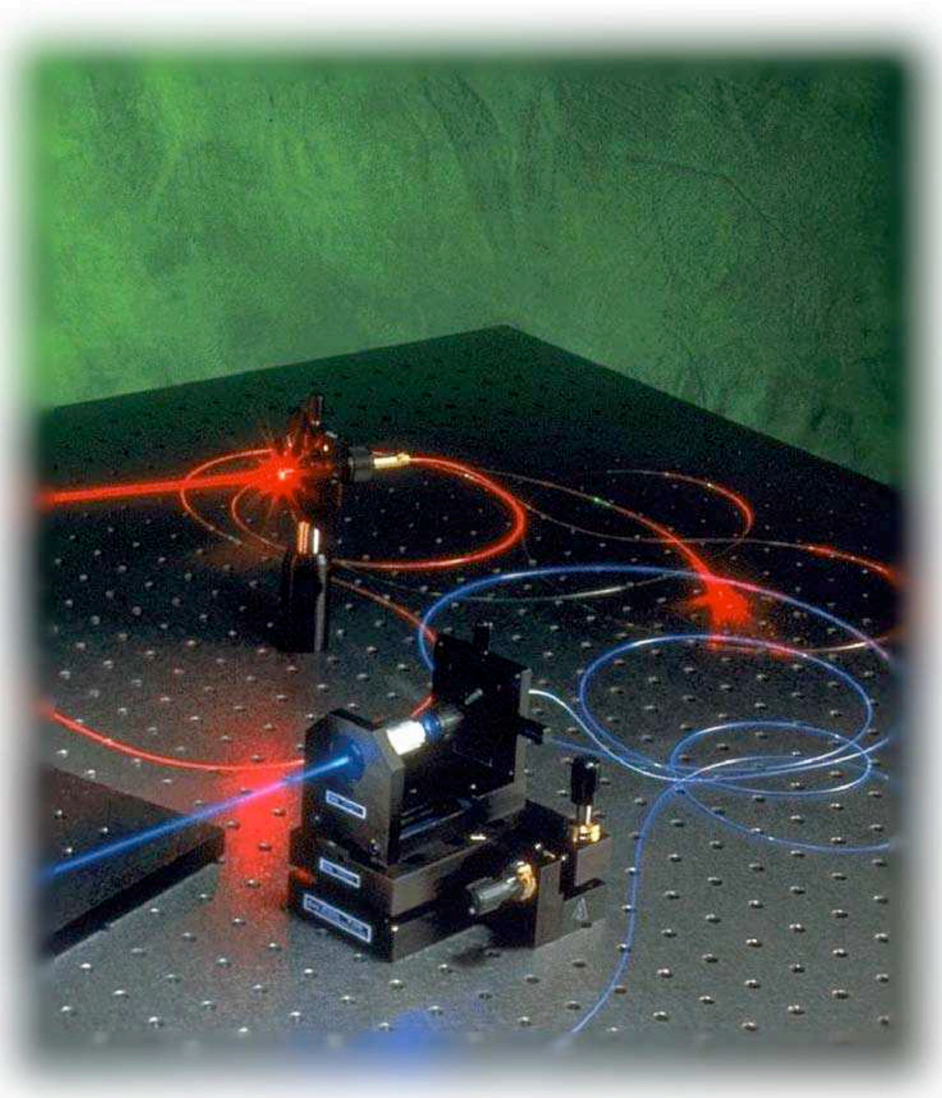
Fiber Optic Speed of Light Apparatus

Instruction Manual



INDUSTRIAL FIBER OPTICS

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INTRODUCTION

Welcome to the fascinating world of fiber optics technology! We believe you will find the instructions and exercises in this science curriculum not only educational, but challenging and enjoyable as well.

This manual is an essential component of the *Speed of Light Apparatus* — which is designed for use in science, physics, industrial technology and vocational education classrooms, grades 10-12. Physics fans and other science-oriented individuals (including those who are just intellectually curious about how things work!) may also obtain the apparatus for studies in home or workshop.

Your particular apparatus may have been purchased either fully assembled at our factory, or in kit form which you can assemble on your own. Easy-to-follow instructions for this kit are contained in the *Assembly* portion of this manual.

The manual is intended to guide both instructors and students through a basic introduction to the principles of fiber optics and the measurement of the speed of light. The apparatus includes one experiment, along with descriptions of components, a glossary of terms commonly encountered in fiber optics, and a list of optional reading references which discuss fiber optics theory and development.

Everything is here for you to get in on the ground floor of fiber optics, to develop an understanding of emerging technology in this vast new field of potential applications, and to ready yourself for more advanced studies.

When you are ready to move on to more sophisticated discussions, look for our other study materials and kits specifically designed to make learning both fun and rewarding.

BACKGROUND INFORMATION

The miracles of modern-day fiber optic technology didn't simply show up on someone's door step. Centuries of curiosity, experimentation, frustration and perspiration passed before pure science won out over superstition and guesswork. A small Italian gentleman was among the first to seek enlightenment about the speed of light . . . .

The Speed of Light – A Centuries-Long Quest

Scientists, and probably even more casual thinkers, began speculating about the speed of light centuries ago. When you consider that early civilizations often made gods and goddesses out of suns, planets and moons, it isn't hard to understand their fascination and wonder about one of the most powerful forms of energy in their world.

One of the first, that we know of, to ask himself, "Hmmm....wonder how fast that stuff travels?" was Galileo Galilei (1564-1642), Italian astronomer and physicist....the same fellow who dropped objects off the now-Leaning Tower of Pisa trying to calculate their rates of fall.

Galileo scored with the tower business, in calculating the fall rates of items as varied as feathers and cannonballs. Light was another matter, however, and he knew he had to attempt his measurements of light speed over a much greater distance if he hoped to get a *whatever*-per-second grip on that speeding luminous energy.

He decided that hilltop-to-hilltop was a good starting point, and that's where he began, with himself on one hill and his trusty assistant on another, well after the sun had set. Each man carried an oil-burning lamp with a cover, so he could shield the light until needed.

Galileo uncovered his lamp briefly, sending a flash of light over to his assistant. The assistant replied, with his own quick flash of light back to the boss. The exchanges continued that night, and many nights more, from hilltops increasingly further apart.

Galileo had hoped to measure the time which elapsed from the moment the lamp shields were uncovered until the light was perceived by his eye. Rotten luck. He finally decided (rightfully) that he and his assistant weren't physically up to the challenge of grappling with an item we now know to travel at 186,000 miles per second. (Incorrectly) he determined that light travels at infinite speed.

Figure 1. Galileo Galilei (1564-1642).

The next recorded method of measuring light was that of Frenchman Armande H. L. Fizeau (1819-1896) in 1849. Try to visualize his elaborate, apparently unwieldy array of mirrors, lenses, and a huge rotating cogwheel with 720 teeth, designed to measure the speed of light over a distance of 5.39, count 'em, miles.

But the thing worked. Pretty much. Fizeau and his apparatus computed light speed at 194,000 miles per second. Not bad, when you consider the scientific tools available at that time, plus the difficulty of the experiment.

In the years that followed, investigators steadily improved on Fizeau's equipment and methods of observation. Most notable was the work of American physicist, Albert Michelson, (1852-1931) who replaced Fizeau's 720-tooth wheel with an eight-sided mirror. (He also increased the measurement distance to 44 miles.)

In 1926, Michelson got a grip on light, computed at 299,796 kilometers per second — or 186,284 miles per second.

The quest for precision, and the continued refinement of the measurement, continued until, today, really only hard-core mathematicians quibble about the number of decimal places we should assign to the speed of light.

The speed of light in a vacuum is now listed as 299,792.4562 kilometers per second. For the purposes of everyday discussion we generally suffice with a figure of 300 million meters per second, or 186,000 miles per second.

Speed Zones Occur When Light Meets Matter

Up to this point, we've talked primarily about light traveling through a vacuum, such as outer space. When light passes through some medium other than a vacuum (such as a gas, solid, or liquid), it slows down. But often not by much.

- At sea level, light speed through air is only about 70 kilometers less per second than it is in a vacuum. (At higher altitudes, where the air is less dense, and where light is impeded less by solid airborne particles, light speed increases.) For most practical purposes we can rate light speed in air versus light speed in a vacuum the same.
- In water, however, things get relatively sluggish. The speed of light is about 25 percent less than in a vacuum.
- In glass, light has even a tougher time. Its speed drops by about 33 percent, compared to its rate in a vacuum.

To put these relationships into some form of mathematical perspective we utilize the term "refractive index" (or "index of refraction") — which refers to the ratio between the speed of light in a vacuum and its speed in some other medium. Here's the equation:

$$\frac{Light\ speed\ in\ a\ vacuum}{Light\ speed\ in\ another\ medium} = Refractive\ index$$

Or, massaging things down into more manageable symbols:

$$\frac{c}{v} = n$$

Substituting the numerical values of light speed in air, water, and glass we would obtain the following refractive indices:

For air: $n = 1.000$
For water: $n = 1.333$
For glass: $n = 1.50$

If we went to five decimal places instead of three, we would find the refractive index for air is actually 1.00029.

Precise? Definitely much more so than in the days of Fizeau, not to mention Galileo. You'll soon learn how we can measure the speed of light with accuracy that would have astounded those well-intentioned gentlemen with their lamps, cogwheels ,and mirrors.

Fiber Optics: Light Meets its Master at Last

The modern-day technology of fiber optics got its start back in the days when tinkerers and scientists were trying their best to bend light around corners. It isn't exactly clear why anyone would want to do that, but a lot of people, even a hundred years ago, were unwilling to accept that light travel was confined to straight lines.

They tried hundreds of schemes — many involving intricate arrangements of mirrors — but no one scored big until 1870 when English physicist,John Tyndall (1820-1893), demonstrated a most impressive principle to members of the British Royal Society.

With a simple apparatus whose major components included a light source, a slender stream of falling water, and a bucket, Tyndall demonstrated that light could be guided inside a most definitely un-straight arc of water. His equipment is represented in **Figure 2**.

Figure 2. John Tyndall's demonstration: Guiding light in water.

Good show! Good show! Tyndall depicted for the first time what now occurs millions of times a day in our high-tech communications industry: Light is **guided** inside some curving medium, and very little is allowed to escape until we're ready to let it go. He used a stream of water. We use slender fibers of glass and plastic.

Sixty-five years after Tyndall's water, light, and bucket demo, Norman R. French, a scientist with American Telephone and Telegraph (AT&T), conceived of and demonstrated the use of light-guiding fibers as a communications device. Proof of the pudding: He was granted a patent for an "optical telephone system" which transmitted voice signals on beams of light through a network of "light pipes."

By the early 1960s, scientists (most working for the phone companies) were right on the doorstep of creating the first fiber optic telephone networks. Three components, in particular, were proving to be increasingly compatible:

- Small, compact Light Emitting Diodes (LEDs)
- Lasers
- Glass optical fibers

Researchers from throughout the world put those items through assorted scientific hoops day after day, year after year, until they arrived at the basis for the largest and most efficient fiber optic telephone communications in existence today.

In 1976, the Bell System installed a trial fiber optic telephone system, and one year later had a commercial system in operation near Chicago. The phenomenal reliability of that system was in large part responsible for the rapid acceptance of fiber optic networks today. Bell's "acceptable" percentage of "outages" or out-of-operation-due-to-failure-time for its existing wire and microwave carrier system was .02 percent. The new fiber optic set-up, even while the bugs were still being removed, had a downtime average of .0001 percent. Small wonder that engineers and financiers alike started thinking: "Fiber optics...hmmm.....sound good....sound very good."

Optical Fiber: The Workhorse Today

Optic fibers are usually made of plastic or glass. Plastic fibers cost less than glass but they lose light more readily. Both consist of two essential layers of transparent optical materials, core and cladding.

Viewed from one end, as in **Figure 3**, the fiber materials appear in cross section as concentric circles, with a common center, or axis, thus the term coaxial. The outer layer is called cladding; the inner layer, which carries the light, is called the core. What makes this little combination workable is the concept we discussed earlier, called the refractive index. The

Figure 3. Cross-section of a typical optical cable.

cladding of an optical fiber has a lower refractive index than that of the core, and that simple difference helps trap light rays within the core, rather than allowing them to wander off into space.

When light enters an optical fiber, it travels in a straight line until it strikes the boundary between core and cladding. At that point, light is deflected back into the core and proceeds once again in a straight line until it strikes the core/cladding boundary again. The process repeats itself time and again, and it permits light to negotiate curves in the fiber by sort of ricocheting its way around the turns.

Whether we're talking glass or plastic, however, one principle works the same for both, and that's a little jewel known as **Snell's Law** – the thing that explains the ricochet-around-the-turns process we described above.

The amount that light bends depends partly on two materials having different refractive indices (as in optical fiber) but it also depends on the **angle** at which the light ray strikes the boundary between the two materials. That "incoming" light ray is known as the **incident** ray, and the "outgoing" light ray which bounces off the surface is known as the **reflected** ray.

Mr. Snell (his full name was Willebrod Snell van Royen), a Dutch mathematician, birth date unknown, explained in 1621 how light is bent, by explaining the relationship between angles of incidence and angles of transmission. **Figure 4** depicts these two angles. Note that both angles are measured from a line drawn perpendicular to the surface, at the point where the incident ray strikes.

Figure 4. Ray of light traveling through two materials.

Here's the equation:

$$\eta_1 \bullet \sin\theta_1 = \eta_2 \bullet \sin\theta_2$$

The η_1 and η_2 are the respective refractive indices of the two materials involved (in an optical fiber these would be the refractive indices of the core and cladding). θ_1 is the angle of incidence; θ_2 is the angle of transmission.

Snell's Law isn't limited to the bending of light, though. It also helps explain how light can be reflected from a surface. That's handy for us, because if light couldn't be reflected, our optical fiber would be just so much excess hose, rather than the communications wonder it is.

When an incident light ray strikes the boundary surface between our two materials at a 90-degree angle, most of that light is going to penetrate the materials and keep on going. The same will be true if the incident angle is very small — say on the order of a few degrees away from the perpendicular.

However, as Snell's law tells us, there is a point — otherwise known as the **critical angle** (when the incident light ray is leaning well away from the perpendicular) — when the incoming light will be totally reflected off the boundary between the two materials, as in our optical fiber. Stated another way: If light traveling through one material encounters another material having a lower index of refraction, and if that light strikes the boundary between the materials at a low-enough, or "glancing" angle, it cannot escape from the first material. This is where we get the term **total internal reflection**, which explains how light is guided in an optical fiber.

There is Always a New Frontier

We've come quite a distance in time and technology since the days when Galileo grappled with the awesome speed of luminous energy. Today, *knowing* the speed of light isn't so important to us as our ability to *control* the way in which light travels. Through the marvels of fiber optics, we have achieved partial control, but we are only on the threshold of new discovery. Just as people in John Tyndall's day wanted to throw a few curves into the flight path of light, you can bet that people today (perhaps even you!) are thinking of ways to disprove old beliefs, to overcome the challenges of the unknown, and to master the mysteries of science with innovation and determination.

ACTIVITY

Using the **Speed of Light Apparatus** and a dual-channel oscilloscope you will be able to measure the speed of light in a transparent medium.***** In this case, the medium is plastic optical fiber.

The transmitter portion of the apparatus generates more than 500,000 light pulses per second, which appear as a cone of red light leaving the red LED. When one end of the fiber is connected to an LED and the other end to a detector or receiver, our red light will make a circular trip through the fiber. The time required for these red pulses to travel through a 20-meter-long fiber is about 100 billionths of a second, or 100 nanoseconds.

A bit on the quick side? Rather. However, with the aid of an oscilloscope, this becomes a straightforward, practical, and visually rewarding demonstration of how an elusive natural phenomenon such as light can be captured (briefly) and measured by people who put their minds to work.

Materials Required for the Project:

Speed of Light Module, which includes:

Speed of Light Apparatus *
110 VAC-to-DC power adapter - use only the one provided
15 centimeters of plastic fiber†
20 meters of plastic fiber†

Required but not included:

Dual-channel oscilloscope, 20-MHz bandwidth or greater
(time-base measurement capability of 0.1 micro-seconds or less)
2 oscilloscope probes

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* If you purchased your Speed of Light Apparatus as a kit, you must first assemble it, following the instructions in the Assembly portion of this manual. If the kit was assembled at the factory, you may proceed with ***Equipment Setup*** following.

† Check the ends of the fiber to see if they are polished and flat. If not, go to the Fiber Preparation section and polish the ends of the fiber cable before going further.

Equipment Setup

1. Turn on the oscilloscope.
2. On the oscilloscope make the following settings:
   - Set the Horizontal Mode Switch on A
   - Set the Triggering Mode on Auto
   - Set the Trigger Source Switch on Channel 1
   - Set Triggering on Positive Slope
   - Set the voltage control of input Channel 1 on 1-volt per division
   - Set the voltage control of input Channel 2 on 0.5-volt per division
   - Set the input coupling of both channels on AC
   - Set the Timebase on 50 nanoseconds per division
   - Set Verticle Mode to ALT.
3. Connect the probe of Channel 1 to the (blue) test point marked "**Reference**" on the Speed of Light Apparatus.
4. Connect the Ground lead of Channel 1's probe to the ground test point just below the **Reference** test point. (It is not essential to use probes with ground leads, but the waveforms on the oscilloscope screen will have better shapes from which measurements can be made.) If your probes do not have ground leads, use the ground on the oscilloscope.
5. Connect the probe of Channel 2 to the "**Delay**" (blue) test point on the apparatus.
6. Connect the ground lead from Channel 2's probe to the ground test point just below the "**Delay**" (white) test point.
7. Move Channel 2's input selector to the "ground" position.
8. Plug the connector of the 110 VAC-to-DC power adapter into the receptacle on the left side of the apparatus. Plug the AC adapter into a 110 VAC 60 Hz receptacle.
9. As soon as the AC adapter supplies power to the apparatus, the yellow LED should light up. **D3**, the fiber optic LED, should also be visible if you lean down to look sideways into the front of the blue fiber optic housing.
10. Turn the "**Calibration Delay**" knob on the apparatus to the 12 o'clock position.
11. Loosen the fiber optic cinch nuts on the fiber optic LED **D3** and detector **D8**.
12. Select the 15-cm length of plastic fiber and insert one end of it into LED **D3** until it is seated, then *lightly* tighten the fiber optic cinch nut.
13. Insert the other end of the optical fiber into detector **D8** until seated, then tighten its fiber optic locking nut.