THE SPEED OF LIGHT

OBJECTIVES

To measure the speed of electromagnetic waves in free-space (air), as they travel through an optical fiber, and/or as they travel through a wave guide.

LIGHT SPEED IN AIR

You have available a diode laser (670 nm wavelength) that can be pulse modulated at very high speeds, a pulse generator, a fast photodiode detector, various mirrors, and a scope.
Part 1: Devise an experiment to measure the speed of light in air.

Notes:
1. To modulate the laser off and on, use the Variable Output of the pulse generator and set the amplitude to ≈5 V.
2. The photodiode has an on/off switch on the back. Please **turn it off** when not in use, and especially when you're done, so as not to run down the little battery inside.
3. The scope input for the photodiode signal should be set to 50 Ω, DC coupled. Room lights are not a problem.
4. For safety reasons, keep the laser beam confined inside Room E12.
5. This is a precise experiment. Your measured value should differ from the accepted value by no more than 1%. A large error indicates a flaw in your experimental design.

The Meter

Actually, you can't really measure the speed of light. Unlike other constants of nature that are known empirically – such as h or e – the speed of light is <u>defined</u>:

$$c = 299{,}792{,}458 \text{ m/s by definition}$$

How can this be?

Prior to 1983, scientists had separate standards for defining the units of time (the second) and length (the meter). But if c – a ratio of length to time – is truly a universal constant, the same in all reference frames, having separate standards for length and time is redundant. This was not a practical issue for many years because neither the standard for the meter nor the standard for the second could be implemented terribly precisely. This changed with the advent of laser technology in the 1960s and 1970s. It then became feasible to define the meter in terms of the second. Thus in 1983 the General Conference on Weights and Measures – the international body that oversees the SI system of units – defined c as above and also defined

1 meter = distance traveled in vacuum by light in 1/299,792,458 second

where 1 second = 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine energy levels in the ground state of ^{133}Cs. The energy-level structure of cesium is just like that of rubidium, which you used (or will use) in the optical pumping experiment, and the measurement of this frequency in ^{133}Cs is done using optical pumping.

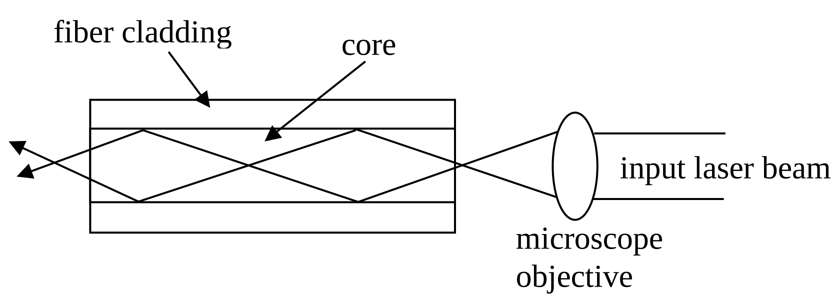
Part 2: With this in mind, use the defined value of *c* to measure the distance between the two lines marked on tape on the lab bench. Compare your result to the distance as measured by a high-quality tape measure. Now in this case, the calibration of the tape measure is probably better than your ability to measure short time intervals, but in principle you could use a very precise time measurement, based on a frequency standard, to make a distance measurement that is vastly superior to the tape measure.

Now do <u>either</u> speed of light in an optical fiber <u>or</u> wave propagation in a wave guide.

SPEED OF LIGHT IN AN OPTICAL FIBER

Light travels through optical fibers by a process of total internal reflection, the light being confined in the high-refractive-index core. Although the exact speed depends on the details of the fiber index distribution as well as the wavelength of the light (and this is very important for long-haul communications systems) a reasonable approximation to begin with is that the light is traveling through glass of refractive index $n \approx 1.5$. The speed of light should then be <u>roughly</u> 2×10^8 m/s. (This is *very* rough, just to give you an idea. <u>Do not</u> use 1.5 as a known refractive index for making comparisons.)

To get light into the fiber, you need to use a microscope objective to focus the laser to a tiny spot on the face of the fiber:



For this to be successful, the fiber needs to be cleaved to have ends that are flat and perpendicular to the fiber axis, not jagged and broken.

The fiber has three parts: the high index core, the lower index cladding and a protective plastic jacket. There will probably be some fiber lengths around, but if you need a new one, you need to strip back the jacket to prepare the fiber. Burning off a small section using a cigarette lighter works. The fiber ends then need to be cleaved to present a flat surface to the incoming and outgoing light. Occasionally, the fiber may break after it has been heated and this break is often good enough quality. Try tugging on the fiber end. If the fiber does not break then put the fiber on a glass surface and apply LIGHT pressure with the diamond scribe. The intent is not to break the fiber with the scribe but to initiate a flaw in the glass, weakening it. Now tug, parallel to the length of the fiber, breaking it.

Place one end of a prepared end in the fiber chuck, focus the laser beam into it (smallest spot size of the focused beam onto the face of the fiber), and look at the output from the other end on a piece of paper. Do whatever you need to do to get an output, then maximize its brightness. Once there's a decent amount of light with good beam quality, direct the output to the photodiode, where you can tweak the input focusing to get maximum output.

Part 3a: Devise an experiment to measure the speed of light through the fiber. Then use your result to determine the index of refraction of the fiber.

SPEED OF ELECTROMAGNETIC WAVES IN A WAVE GUIDE

You've used coaxial cables many times to hook up electronics. If you've never seen "inside," look at the piece of coax that's available for inspection. A coaxial cable –a thin center conductor surrounded by a cylinder outer conductor – is technically a **wave guide**, something you may learn about in PHYS 409. When you apply a signal at one end of a cable, it does not appear instantaneously at the other end. There is a delay as the signal propagates down the cable. But how fast does it go? A signal propagates down a wave guide as an electromagnetic wave moving at a speed that depends on *c*, on the insulation material inside the cable, and perhaps on geometric properties of the cable.

We have a large spool with 1000 feet of coaxial cable, terminated at the "far" end by a resistor box. A cable has what's called a <u>characteristic impedance</u>. If you terminate the cable with a resistor matching the cable's impedance, all of the signal reaching the end will be absorbed by the resistor. If the resistor does not match the cable impedance, some of the signal will be reflected back through the cable toward the source. Depending on whether the resistor is larger or smaller than the cable impedance, the reflected signal may be <u>inverted</u> relative to the source. This is exactly analogous to the "phase shift upon reflection" in optics, where a reflected light wave does or does not have a 180° phase shift, depending on whether the index of the reflective material is larger or smaller than the index of refraction of the incident material. And there's no reflection at all if the two materials have the same index of refraction.

Part 3b: First, measure the characteristic impendence of the cable. Also determine whether the inverted reflection occurs for a termination resistor that's smaller or larger than the cable impedance. Second, measure the speed of electromagnetic wave propagation along the cable. Give your result both in m/s and as a fraction of *c*.

Note: Think carefully, perhaps making some calculations, about the appropriate width and repetition rate of the pulses you send into the cable.