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AN ALTERNATIVE SPEED OF LIGHT MEASUREMENT EXPERIMENT FOR A SENIOR PHYSICS LABORATORY

Abstract

A simple, time-of-flight experiment utilising readily available equipment is described for use in a senior school physics laboratory. A modulated laser is employed with measurements taken over a number of distances. Students obtain a conceptual understanding for the extremely high, but measurable speed of light. The technique of eliminating an unknown constant by making more than one measurement is also introduced. Additionally, students are introduced to the concepts of optics, measurement of very small time intervals, modulation of lasers, waveform generation, fast detectors and data processing.

Introduction

The constancy of the speed of electromagnetic radiation for inertial frames is one of the postulates of the special theory of relativity, which forms one of the corner stones of modern physics. The speed of light is a physical constant of nature with a value in a vacuum of 299,792,458 m s[-1]. In October 1983, the International Committee on Weights and Measures agreed to redefine the standard of length in terms of the speed of light with the metre being the distance travelled by light in a vacuum in an interval of 1/299,792,458 of a second (Beekman, 1983; Rohlf, 1994).

Although defined as a physical constant, the measurement of the speed of light in a senior physics laboratory provides a worthwhile exercise as a number of techniques and principles may be learnt in the process. A number of exquisitely precise measurement techniques have been employed to measure the speed of light (Bates, 1988). Examples of these are:

- Techniques employing independent measurement of frequency and wavelength (Bates, 1983);
- Time of flight measurement methods employing pulsed light-emitting diodes (Ciholas & Wilt, 1987; Trudeau, Loh & Hartman, 1971; Vanderkooy & Beccario, 1973);
- Strobe lamps used with photo cells (Cooke, Martin, McCartney, & Wilf, 1968);
- Spark light source with a photomultiplier tube (Elmore, 1972);
- Gamma ray photons from a radioactive source (Huang, 1971);
- Lasers with a modification of the rotating mirror method (Domkowski, Richardson, & Rowbotham, 1972; Edmonds & Smith, 1971);

- Lasers in combination with electrooptic modulators (Becchetti, Harvey, Schwartz, & Shapiro, 1987);
- Acousto-optic modulators (Carlson, 1996; Deblaquiere, Harvey, & Hemann, 1991);
- Phase comparison methods (Barr & Armstrong, 1990);
- Ghosts on a television (Keeports, 1990; Schroeder & Smith, 1985).

Speed of light apparatus employing the method of modulation of a laser signal is available from several suppliers (Leybold, 1996; Metrologic, 1993-94). This paper presents an alternative speed of light measurement based on the laser modulation method for use in a senior physics laboratory. The experiment described provides a hands-on approach to the measurement of a physical constant. The method provides a conceptual understanding of, and an intuitive feel for, the complexity and difficulty involved in the measurement. Additionally, the method employs a number of increasing distances and the increasing time of flight between a reference beam and a beam that has travelled over the distance provides an understanding of the finite yet extremely high speed of light. The students are introduced to the concepts of optics, measurement of very small time intervals, lasers, oscilloscopes, modulation of lasers, waveform generation, fast detectors and data processing.

Experimental

The equipment is arranged as shown schematically in Figure 1 and a photograph provided in Figure 2. The method uses a modulated 0.95 mW laser diode transmitter and a receiver (model LD1-DM-SOL, Laser Services, Nerang, Australia) that are Australian made and of approximate price $600. The laser beam is potentially harmful if permitted to enter the eye directly, so it is necessary to instruct the students not to look directly down the laser beam. The laser beam is modulated with a triangular wave from a signal generator (Hameg, HM8030-5) with an approximate cost of $1,000. The electronics for modulating the laser are internal to the laser, contributing to a less complicated experimental setup. The output of the signal generator also triggers the two channel, digital, real time oscilloscope (Tektronix TDS 220) with approximate cost of $2,000. Any model of signal generator or fast oscilloscope will be suitable. The amplitude and frequency of the modulating signal are fine tuned to obtain the maximum modulation. In this experiment a frequency range of 250 to 500 kHz provided good results.

This modulated laser beam is transmitted over a number of measured distances in the laboratory. The doors of the laboratory are closed to minimise wind currents and other air disturbances. A number of distances are obtained by reflecting the laser beam from up to a maximum of five front surfaced mirrors. These mirrors are mounted on Leybold stands to allow fine adjustment of the mirror angle. Figure 1 shows the laser beam travelling over the path length of 47.5 metres with reflections off three mirrors, M 1, M2 and M3. Other distances can be achieved by using one, four or five mirrors and also by moving mirrors M 1 and M2, which are furthest from the laser. In this way, time of flight measurements can be made over a number of distances.

The receiver can be moved vertically by means of a laboratory jack. The reflected laser beam is focused for each of the distances with a converging lens to the same point on the receiver. The signal from the detector is input to channel two of the oscilloscope and the reference beam and the reflected beam displayed. As the travel distance increases, the time delay of the reflected beam increases providing an understanding of the finite value for the speed of light. This is repeated for all distances. For each distance, the signal generator frequency, time base on the oscilloscope and the degree of focusing of the beam onto the detector remained fixed in order to maintain consistency.

The time difference between the reference beam and the reflected beam are determined with the use of the calibrated time base of the oscilloscope. There are a number of unknown phase shifts in this experiment, namely, the phase shifts in the electronics involved in the laser modulation and in the detector and also in the connecting cables. These unknowns will remain constant for each of the distances over which the experiment is performed and a plot of the time difference versus distance will produce a straight line. A least squares fit produces the line of best fit and the speed of light is provided from the inverse of the slope.

Sample results

A photograph of a typical display on the oscilloscope is shown in Figure 3. The pulse directly from the signal generator is the sharp triangular pulse and the output of the detector from the return laser beam after traversing a measured path length is the broader pulse. With the digital oscilloscope, it is possible to "freeze" the screen and position the two cursors shown as the vertical lines in Figure 3 on the peaks of the reference and reflected signals. The time difference is provided on the right hand side of the display in the box marked "Delta", namely 400.0 ns in this example. If a different type of oscilloscope is employed, the calibrated time base can be used to determine the time difference.

Figure 4 shows the time differences for the five path lengths plotted as a function of distance along with the least squares line of best fit. The slope of the line is 3.369×10^{-9} s m^{-1} with an R-squared value of 0.9976. The intercept on the y axis for a distance of zero is non zero and represents the time delay in the system. The speed of light is the change in distance divided by the change in time and is obtained from the inverse of the slope of the line, namely, c = 2.97x108 m s^{-1}. In this experiment, the largest source of error is the uncertainty in measuring the position of the peak of the reflected signal, however, this is minimised by taking a series of measurements over a number of distances.

Discussion

By taking measurements over several distances, students obtain a conceptual understanding for the extremely high, but measurable speed of light. Conceptually, this experimental set-up is easy for the student to grasp and does not have a "black box" approach associated with it.

Another advantage is that the equipment is simple and would be available at many high schools and each individual item of equipment may be employed in many other physics and science experiments. The technique of eliminating an unknown constant by making more than one measurement is also introduced. This is an important tool for experimental physicists. The students can arrange the equipment with minimal supervision and obtain a realistic value for the speed of light while gaining an understanding of the principles involved.

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DIAGRAM: Figure 1. Schematic diagram of the experimental arrangement

PHOTO (BLACK & WHITE): Figure 2. Photograph of the laser transmitter and receiver, signal generator and digital oscilloscope

DIAGRAM: Figure 3. Photograph of a typical display on the dual trace oscilloscope showing the sharp triangular pulse from the signal generator and the signal of the reflected beam

GRAPH: Figure 4. Plot of the time differences as a function of the path length travelled

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