Speed of Light Measurement with a Simple Way

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Abstract— A method for a measurement of the speed of light is described. It is used a combination of simple, low-cost experiments. We will try to measure the wavelength and frequency of light and then we will determine the speed of light using the fundamental equation of wave. The measuring of wavelength based on the phenomenon of light interference or the phenomenon of light diffraction. The measuring of frequency based on the fact that the energy of a photon is proportional to the voltage needed to cause electrons to flow. The experiments are accessible to upper secondary school (or to college) students and particular to non-major science or engineering students. Experimental setup and equipment details are given. Also limitations of the method and experimental results are analyzed.

Index Terms—Speed of Light; Measurement; Experiments; Interference; Diffraction; Photon Energy; Laser; LED.

I. INTRODUCTION

The speed of light is one of the most fundamental constants in physics. The SI (System International) definition of the meter (1983 Conference Generale des Poids et Mesures), is: “The meter is the length of the path travelled by light in vacuum during a time interval of $1/299,792,458$ of a second”. So the definition of the speed of light c , in vacuum is exactly $299,792,458$ m/s. This is the fastest speed that information can travel.

Therefore, it is highly desirable to have a method with simple, low-cost experiments to measure the speed of light. The experiments and the technic we present have the following requirements:

- The experiments concept is quite comprehensible to students with high background in mathematics (non-science and non-engineering majors).
- The experiments can be performed easily
- There is safety and no difficulty, for the students, during the conduction of the experiments.
- The accuracy of the measurement is very good (even though clarity is more important than precision).
- The experimental setup is cheap (low budget experiments).

All the above requirements have been satisfied with the proposed experiments. Many experiments to measure the speed of light have been presented. We can mention briefly some of them. For the measurement of the group velocity of light (in transparent media) is described an apparatus. It is used a modified He-Ne laser as a light source. Results for the velocity of light in air have been obtained with the aid of an oscilloscope [1]. An undergraduate laboratory is

described that combines a fundamental investigation of a basic laser system and a measurement of the speed of light with high accuracy [2]. A paper reports on a student experiment at the intermediate undergraduate level for determination of the speed of light. Harmonic mixing is utilized for the frequency determination and interferometry for the wavelength determination of a 9-GHz electromagnetic source [3]. Using a laser pointer (as the signal carrier) with adjustable focus, a signal generator for modulation of the light beam and an oscilloscope for the phase shift detection is measured the speed of light [4]. However, it is very difficult to find any experiment that satisfied all the requirements. Our experiments are quite inexpensive, simple in order to be accessible to upper secondary school (or to college) students, and particular to non-major science or engineering students. Also the experiments should be presented even in primary school as demonstration experiments and the method of measurement the speed of light as an oral presentation.

This proposed method for the experimental measurement of the speed of light shows that it is possible to obtain low cost activities for more sophisticated topics (such as the light speed measurement). Also our method helps students to increase their understanding of the specific topic (and general in physics concepts) as they have an active role in the learning procedure (they construct measure and manipulate the apparatus).

II. METHOD

We will try to measure the frequency and wavelength of a laser beam (or an LED) and then we will determine the speed of light using the fundamental equation of wave: $c = \lambda f$.

The measuring of wavelength based on the phenomenon of light interference (double-slit experiment) or the phenomenon of light diffraction (using a CD as a reflection grating). From the geometry of the experimental setup we find the value of λ .

The measuring of frequency based on the fact that the energy of a photon is proportional to the voltage needed to cause electrons to flow. The electric energy E of a photon emitted is proportional to the electric charge e of an electron (constant with absolute value $e = 1.6 \times 10^{-19}$ Coulomb) and proportional to the voltage V required to light a laser or an LED. The expression is: $E = eV$. Also the photon energy is $E = hf$ where f is the frequency and h is Planck's constant $h = 6.63 \times 10^{-34}$ J sec [5], [6].

In this method we calculate the wavelength of the red light using a red laser pointer and the frequency of the red light using an LED. This happens because the laser light gives better results (clear separated fringes) for wavelength calculation and the LED gives an easy experimental set-up

for frequency calculation. This is allowed because the light frequency characterizes the light color (certain frequency corresponds to a certain color) irrespective of the source of light production.

III. THE EXPERIMENTS

A. Experiment for the calculation of the wavelength of light

The materials needed for the experiment are: battery 4.5V, laser pointer, potentiometer 1K Ω as voltage divider, breadboard, cables, digital voltmeter, film with double-slit, screen - a piece of white cardboard, ruler, millimeter paper, pencil, CD, tape measure [5].

1) The double-slit experiment in the case of light (Young's experiment)

Fig. 1. Geometrical description of the double-slit experiment (not to scale; in real situations $y \ll L$)

The condition for bright fringes is (Fig. 1):

$$r_2 - r_1 = d \sin \theta = n\lambda \quad (n=0, \pm 1, \pm 2, \dots)$$

If $y \ll L$, then

$$\sin \theta \approx \tan \theta \approx y/L$$

Thus

$$\lambda = \frac{dy}{nL} \quad (1)$$

Using the (1), we can calculate the value of the wavelength of light by measuring the d , y and L . If y is the distance between the centers of the central bright fringe and the next one, then $n=1$.

Students carry out the double-slit experiment by using monochromatic light. They observe the interference fringes and experimentally find the wavelength of light by using the formula

$$\lambda = \frac{dy}{L} \quad (2)$$

d = the distance d between (the centers) of the slits

y = the distance between the centers of the central bright fringe and the next one

L = the distance between the slits and the screen

The steps of the experiment

- A. The specific double-slit was designed on a computer and then converted into a film by a graphic arts studio. A picture of the double-slit taken by using an optical microscope 350x is given to students (Fig. 2). In the picture, students can also see the double-slit in comparison to a line segment of 200 μm and they have to measure, by using a ruler, the distance d between (the centers) of the slits. (A typical measurement is 80 μm .)

Fig. 2. The double-slit when viewed through a microscope

- B. Students prepare the experimental setup (Fig. 3).

Fig. 3. Apparatus used in the double-slit experiment

The source of light is a red laser pointer (Fig. 4). It can be used a laser of other color (eg. green). The screen is covered by millimeter paper for easier measurements between the fringes (Fig. 5). It is important that the room or lab where the experiment is performed be quite dark.

Fig. 4. Illuminating the slits with a laser pointer

Fig. 5. The interference pattern on the screen

- C. Students mark the centers of the fringes with a pencil. Then, they measure, helped by the millimeter paper, the distance y between (the centers of) the central bright fringe and the next one, for some different distances L . The distance L between the slits and the screen is measured with a tape measure.
- D. Students, using (2), calculate the value of λ for every distance measurement and then the mean $\langle \lambda \rangle$. (Typical measurements: $L=1.6\text{m}$, $y=13\text{mm}$, thus $\lambda=650\text{nm}$)

2) Diffraction of light by using a CD as a reflection grating

Since the surface of a CD has a spiral grooved track, it can act as a reflection grating. The light reflecting from the regions between the closely spaced grooves interferes constructively only in certain directions [7].

If a monochromatic beam of light passes through the hole in the center of a screen and is reflected onto a CD whose surface is parallel to and in front of the surface of the screen (Fig. 6), then a diffraction pattern will be visible in the screen.

Fig. 6. Geometrical description of the diffraction experiment (not to scale)

The steps of the experiment

- A. The information that the CD includes 625 tracks/mm is given to students. Then they have to calculate the distance d between the tracks. (A typical answer: $d=1\text{mm}/625=1.6\mu\text{m}$).
- B. Students prepare the experimental setup (Fig. 7). The source of light is a red laser pointer (the one used in experiment 1). The screen is a piece of white cardboard, in the center of which a hole has been cut.
- C. Students move the CD appropriately so that the central bright fringe ($n=0$) is on the hole and in the middle of the distance between the first-order ($n=\pm 1$) bright fringes (Fig. 8).

Fig. 7. The apparatus used in the diffraction experiment

- D. Students mark the centers of each fringe with a pencil, and then measure the distance y between the central and the next bright fringe by using a ruler. The distance L between the CD and the screen is measured with a tape measure. (Typical measurements: $L=30\text{cm}$, $y=13.5\text{cm}$)
- E. Using (2) above, students calculate the wavelength λ . (A typical answer given the above measurements is $\lambda=656\text{nm}$)

Fig. 8. The central and the first-order bright fringes

B. Experiment for the calculation of light frequency

Like all EM waves, light transports energy across space. This energy, however, arrives at a receiver not continuously but in discrete units called photons. Photons are the particles of light. Photons have no mass, but they have energy $E = hf$. Here h is Planck's constant.

In this experiment we calculate the frequency of the red light of an LED instead of the red light of a laser, as it is easier the set-up and the measurements of this experiment with the LED [6]. Also the light frequency characterizes the light color (corresponds to a certain color).

The materials needed for the experiment are: battery 4.5V, breadboard, cables, digital voltmeter, spectrometer, resistor 220Ω , LED [5].

The steps of the experiment

- A. Implementation – design of the circuit. Students prepare the circuit (Figure 9). The materials used are: a 4.5 Volt battery ($V=4.5\text{ Volt}$), a 220Ω resistor ($R=220\Omega$ with power $1/4\text{ Watt}$) and an LED (D) of red color. It can be used an LED of other color (e.g. green if a green laser is used in first experiment). The resistor is used for the LED protection from high currents and for minimizing the LED current and

voltage.

Fig. 9 The circuit with LED

- B. Measurements of voltage across LED. Students measure, using a voltmeter, the voltage across the leads of the LED (Figure 10). (A typical answer given for the above measurement and for red LED is $V = 1.77$ Volt).
- C. Finding the energy from the voltage (the LED emit). Students calculate the energy of the light emitted by the LED using the expression: $E = eV$. (A typical answer, using $V = 1.77$ Volt, is $E = 1.77$ eV or 2.83×10^{-19} Joule).

Fig. 10 Circuit and measurements of voltage across LED

Fig. 11 The experiment

- D. Calculation of frequency. Students calculate the frequency of light. We have $hf = eV$ so $f = eV / h$ (A typical answer, using $e = 1.6 \times 10^{-19}$ Cb and $h = 6.63 \times 10^{-34}$ J sec, is $f = 4.41 \times 10^{14}$ Hz).

IV. CALCULATION OF THE SPEED OF LIGHT

Students calculate the speed of light c from the expression $c = \lambda f$ using for λ and f the values – answers from the above experiments. Thus we have:

$$\begin{aligned} \text{1st experiment: } \lambda &= 650 \text{ nm} = 650 \times 10^{-9} \text{ m} = 6.50 \times 10^{-7} \text{ m} \\ \text{or } \lambda &= 656 \text{ nm} = 656 \times 10^{-9} \text{ m} = 6.56 \times 10^{-7} \text{ m} \end{aligned}$$

$$\text{2nd experiment: } f = 4.41 \times 10^{14} \text{ Hz}$$

$$\text{So } c = \lambda f = 6.50 \times 10^{-7} \text{ m} \times 4.41 \times 10^{14} \text{ Hz} = 2.8665 \times 10^8 \text{ m/s}$$

$$\text{or } c = \lambda f = 6.56 \times 10^{-7} \text{ m} \times 4.41 \times 10^{14} \text{ Hz} = 2.9296 \times 10^8 \text{ m/s}$$

The right value is about 3×10^8 m/s or with more accuracy $299,792,458 \text{ m/s} = 2.99792458 \times 10^8 \text{ m/s}$

The value of the speed of light in air measuring with our method-experiments is very close to the right value. The results from the above calculations ($c = 2.8665 \times 10^8 \text{ m/s}$ and $c = 2.9296 \times 10^8 \text{ m/s}$) are very close to the theoretical value ($c = 2.99792458 \times 10^8 \text{ m/s}$). The percentage difference (error) is about 4% at the first calculation and 2% at the second.

V. CONCLUSION

We can conclude that the experiments are successful because they satisfy the initial requirements for low cost, easiness, safety and accuracy. The results from the experimental values are very close to the theoretical value.

If we repeat the experiments using laser and LED of other colors (e.g. green) or changing a parameter, for example the distance d between the centers of the slits or the distance L between the slits and the screen at the first experiment we are able to have more experimental values (making of course the necessary calculations). Taking the mean value of all these values of the speed of light we will have a more stable evaluation of the proposed experimental method and its accuracy (or the error between experimental and theoretical value).

Students are able to conduct the experiments during one laboratory period of two hours, obtaining a very good value of the speed of light. Also the simplicity and the low cost of the experiments allow the multiplicity of the experimental set-up and subsequently the division of students into several groups that can work simultaneously during class time taking measurements.

The proposed experimental method shows that it is possible to obtain low cost, active learning activities avoiding expensive kits and allowing students build the experimental set-up, measure and calculate as scientists do.

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