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Speed of light measurement with a picosecond diode laser and a voltage-controlled oscillator

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This work describes an experimental method for measuring the speed of light in air. It uses optical feedback from a visible picosecond diode laser operated below the threshold and a voltage-controlled oscillator to determine the time required for a pulse to travel a known distance. The experimental setup is compact, fitting into a space of $1 \times 0.5\,\mathrm{m}^2$, and at the same time, can determine the speed of light with an uncertainty of 0.03%. The method does not require fast detectors or oscilloscopes.

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I. INTRODUCTION

In a previous paper, I described a method for measuring the speed of light in air using the feedback from a 50-ps pulsed diode laser triggered by a fixed and stable oscillator of frequency 80 MHz.[1] A beamsplitter that reflects a portion of the laser beam to the laser can cause optical feedback, which can increase the average output power of the laser when it is operating below threshold. Feedback occurs in pulsed lasers when an emitted pulse is reflected back into the cavity and overlaps with another pulse inside the cavity. When the distance between the laser and the beam splitter (labelled l in Fig. 1) is an integer multiple of half the separation between successive laser pulses, a reflected pulse encounters a generated pulse at the laser. For a laser operating below the threshold, feedback occurs over a much narrower distance than the spatial width of the laser pulse itself, which is about 15 mm for a pulse of 50 ps duration. Thus, one can accurately measure the speed of light in air v by finding the positions at which the average power of the laser peaks due to optical feedback

$$v = \frac{2l_m}{m} f. \tag{1}$$

Here, $m = 1, 2, 3\ldots$, and l_m is the corresponding distance between the laser and the beamsplitter when the feedback signal peaks. For $f = 80\,\mathrm{MHz}$, $l_1 = 1.88\,\mathrm{m}$, $l_2 = 3.75\,\mathrm{m}$, and $l_3 = 5.62\,\mathrm{m}$. Since the laser is small and located inside its container, it is hard to accurately measure the distance from the beamsplitter to the laser. One needs at least to observe optical feedback at two different beamsplitter positions to eliminate the need to measure distances from the laser. For example, using the positions of the first two occurrences of the feedback signal, one can determine the speed of light from $v = 2(l_2 - l_1)f$. Only the difference between the locations of the beamsplitter when feedback occurs is required.

This paper presents a method to measure the speed of light by employing the feedback from a pulsed picosecond diode laser triggered by a voltage-controlled oscillator. The advantage of using a variable frequency oscillator over a fixed frequency one is that it enables determining the peak of the feedback signal by scanning the oscillator frequency at a fixed beamsplitter position instead of scanning the beamsplitter position at a fixed oscillator frequency. It is usually easier to change the frequency of an oscillator than to change the location of a beamsplitter on a motorized linear stage. Also, a variable frequency oscillator is much cheaper than a motorized linear stage. Additionally, unlike a fixed-frequency oscillator where only one beamsplitter position satisfies Eq. (1) for $m = 1$, multiple beamsplitter positions can fulfill Eq. (1) for $m = 1$ for a variable-frequency oscillator. Thus, one needs only to know the relative distances between these beamsplitter positions for $m = 1$ without needing to use data for $m = 2$ to eliminate the need to measure the distance to the laser, resulting in a compact setup of a length of about 1 m for pulse frequencies in the range of 75 MHz. As in the method of a fixed-frequency oscillator, this method does not require fast detectors or oscilloscopes. The work in this paper is suitable as an experiment for an undergraduate lab or an independent student project. In addition to measure the speed of light in air accurately, by doing this experiment, students may also learn more about pulsed diode lasers, variable-frequency oscillators, frequency counters, computer interfacing, and error analysis.

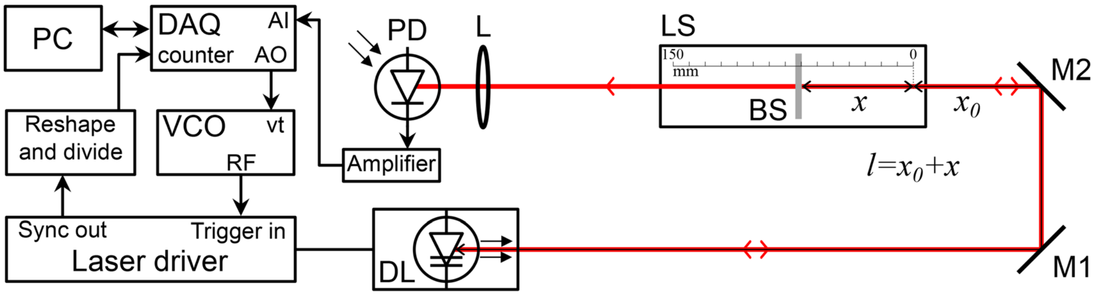

Fig. 1. A schematic diagram of the setup for measuring the speed of light with picosecond diode laser DL, slow photodiode PD, and voltage-controlled oscillator VCO. The red line represents the laser beam. The distance between the laser and the beam splitter is l, which is the sum of the linear stage reading x and the distance between the laser and the beam splitter when the linear stage reading is zero x_0.

II. EXPERIMENT

Figure 1 shows a diagram of the experimental setup. Mirrors M1 and M2 steer the beam of picosecond laser DL to beamsplitter BS, which is positioned on linear stage LS. The beamsplitter partially reflects the laser beam to the laser and transmits the rest through lens L to photodiode PD. The laser beam needs to be parallel to the axis of translation of linear stage LS. The alignment requires replacing beamsplitter BS with an iris and then adjusting mirrors M1 and M2 so that the incident beam passes through the center of the iris at both extremes of the stage's motion range.

The laser generates picosecond pulses of a typical full width at half maximum (FWHM) of 50 ps, equivalent to a spatial width of 15 mm. The maximum possible laser pulse frequency is 80 MHz. For a laser pulse frequency near 75 MHz, optical feedback can occur for a distance of about 2 m between the laser and the beamsplitter. Mirrors M1 and M2 make the setup compact, fitting into a space of $1 \times 0.5\,\mathrm{m}^2$. A voltage signal from data acquisition device DAQ on voltage-controlled oscillator VCO, which triggers the laser driver, determines the frequency of the laser pulses. At a fixed beamsplitter position, voltage-controlled oscillator VCO changes the frequency of the laser pulses in small steps while detector PD measures the average laser power. The power becomes maximum at a frequency whose period equals the time a pulse needs to travel from the laser to the beamsplitter and back again. To eliminate the need to measure distances from the laser, one needs to find the frequency that maximizes the laser power for at least one additional position of the beamsplitter.

In principle, a counter of a data acquisition device can find the frequency of the laser pulses accurately by counting the electric pulses from the synchronization signal output (Sync out) of the laser driver. However, the Sync out of the laser is not compatible with the input of our data acquisition device. The Sync out of the laser driver follows the NIM standard of the levels of fast negative logic signals, while the counter input follows the TTL standard. Also, the frequency of laser pulses, about 75 MHz, might be too high for a data acquisition device. Figure 2 shows a reshaping and dividing circuit used to convert the sync output of the laser driver to a TTL signal and divide its frequency by 2, 4, 8, or 16. It consists of two ICs: MC10H125 quad MECL-to-TTL translator and SN74F136A synchronous 4-bit binary counter.

The following are the models of the components used in the experiment. These specific models were chosen because they were already available in our lab, and other less expensive models might be suitable alternatives. Diode laser DL is a commercial picosecond diode laser system consisting of a head (LDH-P-C-650, PicoQuant) and driver (PDL 800-B, PicoQuant). It emits a collimated visible beam at a wavelength of 657 nm consisting of 50-ps pulses with a repetition rate up to 80 MHz and an average power up to 6 mW. Voltage-controlled oscillator VCO (CRBV55CL-0072-0076, Crystek corporation) has a nominal frequency range between 72 and 76 MHz and tuning voltage between 0.3 and 3.3 V. The two mirrors (BB1-E02, Thorlabs) and the 50/50 beam splitter (BSW10, Thorlabs) are mounted on kinematic mirror mounts (KM100, Thorlabs). Linear stage LS (NST150/M, Thorlabs) is a motorized stage having a travel length of 150 mm and is driven by a stepper motor driver (DRV8824, Pololu). The experiment can be carried out without much difficulty using a manual linear stage. Photodiode PD

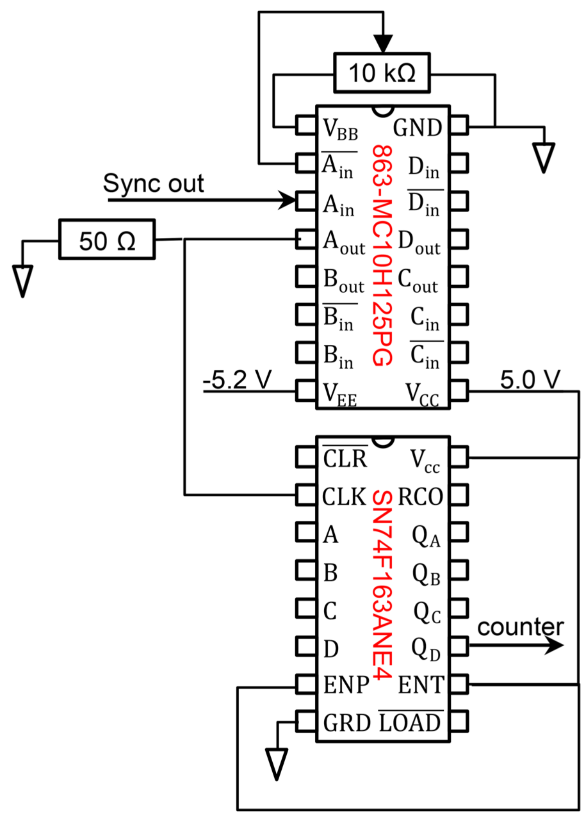

Fig. 2. A reshaping and dividing circuit for converting the sync output of the laser driver from NIM to TTL compatible signals and for reducing the pulse frequency by a factor of 2, 4, 8, or 16. The 10-kΩ potentiometer is a voltage divider to provide bias for the differential input $\overline{A_{in}}$, and the 50-Ω resistor prevents pulse reflection due to the high impedance of the CLK input.

Table I. Bill of materials.

Item	Description	Make	Price
1	Picosecond laser	Head LDH-P-C-650, PicoQuant Driver PDL 800-B, PicoQuant	$10,000[a]
2	Voltage-controlled oscillator	CRBV55CL-0072–0076, Crystek corporation	$130[b]
3	Photodiode	DET36A, Thorlabs	$130
4	Linear stage	NST150/M, Thorlabs	$2,500[c]
5	Data acquisition device	USB-6366, National Instruments	$7,700[d]
6	Stepper motor driver	DRV8824, Pololu	$10
7	Kinematic mirror mounts	KM100, Thorlabs	$40 × 3
8	Beamsplitter	BSW10, Thorlabs	$100
9	Mirrors	BB1-E02, Thorlabs	$80 × 2

[a]A homemade picosecond diode laser can be built for a few hundred dollars (Refs. 2 and 3).
[b]The cost of unmounted oscillator is $30.
[c]The experiment can be carried out with a manual linear stage or with no linear stage.
[d]Any data acquisition device capable of measuring frequency up to 5 MHz such as NI USB-6210, which costs about $900.

(DET36A, Thorlabs) has an active area of 3.6×3.6 mm, and its current is amplified by a transimpedance amplifier (DLPCA-200, Femto). As only a slow response is measured, a resistor with an appropriate value that does not saturate the detector can replace the transimpedance amplifier. Data acquisition device DAQ (USB-6366, National Instruments) and LabVIEW code control the voltage-controlled oscillator, drive the linear stage, count the pulse from the reshaping and dividing circuit, and measure the voltage of the photodiode. Table I lists the costs of the items used in the setup.

III. RESULTS AND DISCUSSION

Before collecting data for the speed of light measurement, it is helpful to find the laser threshold. Also, it is necessary to understand the effect of laser operational conditions on the range of pulse frequencies over which the laser power is affected by optical feedback. The accuracy of the speed of light measurement depends on the ability to determine precisely the pulse frequency that maximizes the laser power. The pulse frequency range becomes very narrow below the laser threshold, which helps in accurately determining the pulse frequency that maximizes the power.

A 10-turn intensity potentiometer sets the power of our laser. With no beamsplitter in the path of the laser beam and hence no feedback, Fig. 3 shows the dependence of the signal of photodiode PD, which is proportional to the laser power, on the intensity potentiometer setting. The threshold occurs at a potentiometer setting of about 6.8.

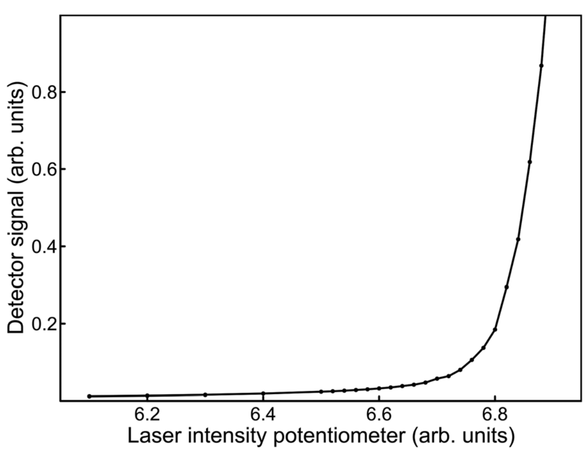

Fig. 3. The detector output, which is proportional to the laser power, versus the setting of the potentiometer of the laser driver PDL 800-B that controls the laser power. The laser pulse frequency is 73 MHz.

The frequency of the laser pulses is measured using the synchronization signal from the laser driver unit. The electric pulses from the synchronization signal output are divided by 16 and then counted by the data acquisition device over a specific time duration. The counting time may affect the accuracy of the frequency measurement, and there is a range of durations for which the accuracy is optimal. For short counting times, the length of the counting time itself limits the accuracy, while for very long counting times, low-frequency drifts in the oscillator are the limit. The small drifts in the voltage controlling the oscillator and the room temperature are the principal causes of the small and slow frequency drifts.

The length of counting time can limit the accuracy, because an error of missing one pulse can occur when counting over a fixed duration.[4] For instance, for measuring a pulse frequency divided by 16 using a counting time of 0.1 ms, the error in frequency measurement caused by missing one pulse can be as high as $16 \times 1/(0.1\,\text{ms}) = 0.16\,\text{MHz}$. Table II shows the average and standard deviation for 100 pulse frequency measurements for different counting times. The table shows that up to a counting time of 500 ms, the error in frequency measurement due to drift is smaller than the maximum error expected from missing one count during the counting time. We choose to work with a counting time of 50 ms, because

Table II. Average and standard deviation for 100 pulse frequency measurements for different counting times. The reshaping and dividing circuit divides the original frequency, 75 MHz, by 16.

Counting time (ms)	Frequency average (MHz)	Frequency standard deviation (MHz)	Maximum error for missing one count (MHz)
0.1	75.008	0.064	0.16
1.0	75.0078	0.0016	0.016
10.0	75.00798	0.00043	0.0016
20.0	75.00793	0.00023	0.0008
50.0	75.00789	0.00015	0.00032
100.0	75.007822	0.000055	0.00016
500.0	75.007759	0.000030	0.000032

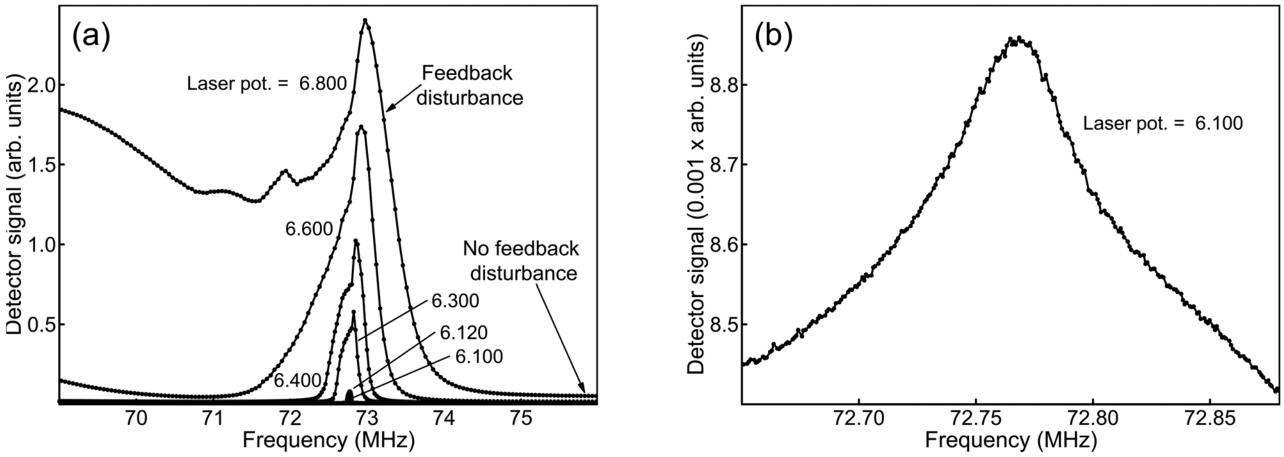

Fig. 4. (a) The detector output as a function of the pulse frequency for a fixed position of the beamsplitter and different laser intensity potentiometer settings. (b) A magnified view of the curve for the potentiometer set at 6.100.

the uncertainty in its frequency measurements is much smaller than that of reading the pulse frequency at which the feedback signal peaks, which is 0.002 MHz, as will be shown later. Also, a counting time of 50 ms provides a relatively short collection time for the signal of the photodiode as a function of the pulse frequency. Since the measurements of the pulse frequency and the detector signals are simultaneous, the small and slow drift in frequency the oscillator might experience does not affect the speed of light measured value.

The beamsplitter needs to be carefully aligned to reflect the laser beam back to the laser. The laser is set slightly below the threshold, so the beam remains easily visible but not potentially harmful to the eyes. For rough visual alignment, the beamsplitter should guide the reflected laser beam back to the laser. This rough alignment can be improved by finetuning the pointing of the beamsplitter when a peak is found while scanning the pulse frequency.

Figure 4 shows the photodiode signal as a function of the pulse frequency for different laser intensity potentiometer settings for a fixed beamsplitter position. The detector output is the time average over many laser pulses and is proportional to the average laser power. One might expect that the disturbance in laser power would occur whenever the generated and reflected pulses overlap. Since their full width at half maximum is $\Delta t \approx 50$ ps, the disturbance would be measured for l's within the range $\Delta l = v\,\Delta t$. From Eq. (1), with $f \approx 73$ MHz, the $m = 1$ feedback disturbance would have width

$$\Delta f = \frac{v}{2}\frac{1}{l_1 - v\Delta t} - \frac{v}{2}\frac{1}{l_1 + v\Delta t} \approx 4f^2\Delta t \approx 1\,\text{MHz}. \qquad (2)$$

Optical feedback is a nonlinear process. When the laser is near or above the threshold, the feedback from the tail of the pulse is large enough to cause power disturbances over frequency ranges exceeding 1 MHz, as in Fig. 4(a). When the laser is operated well below the threshold, power disturbance ranges become much narrower than the 1 MHz range. Figure 4(b) shows that at a potentiometer setting of 6.100, it is possible to determine the frequency at the peak power within 0.002 MHz.

Unlike continuous-wave laser operations, where the gain is always less than the loss below the threshold, in pulsed operations, the laser gain can exceed the loss over a short time below the threshold. When the reflected pulse falls on the laser while the laser gain exceeds the loss, the generated pulse becomes more amplified. The duration of the time, for which the laser gain is larger than the loss, becomes shorter and shorter as the laser operation point moves lower and lower below the threshold. Reference 1 provides a detailed mathematical description of the effect of optical feedback on pulse generation.

For eight different frequencies, the translation stage was adjusted to find the position x at which the feedback signal reached a maximum. The feedback distance $l_1 = x_0 + x$, where x_0 is a constant (unmeasured) offset distance. x_0 is the distance between the laser and the beamsplitter when the position of beamsplitter on the linear stage is zero. For each beamsplitter position, the beamsplitter needs to be adjusted slightly to make the reflected beam fall back into the laser. Also, the intensity potentiometer needs to be adjusted slightly to make the size of the feedback disturbance signal optimal for accurate determination of its peak frequency.

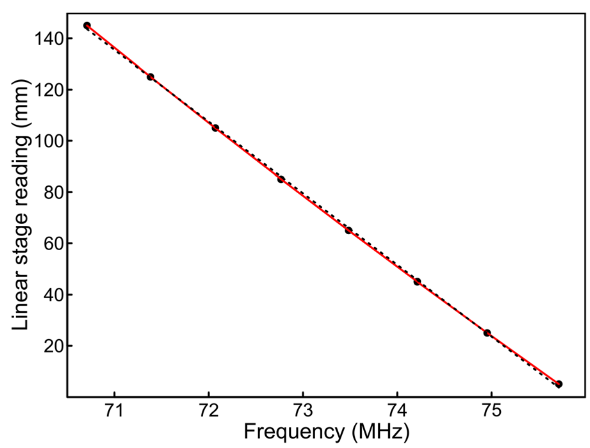

Fig. 5. The position of the beamsplitter on the linear stage as a function of the pulse frequency at which the feedback signal peaks. The solid red line connecting the data points is a non-linear fit according to Eq. (3), and the dashed line is a linear fit. The apparent linearity of the data is because the range of measured frequencies is much smaller than the frequencies themselves.

The red solid line connecting the data points in Fig. (5) is a non-linear fit to the following relation, obtained from Eq. (1)

$$x = -x_0 + \frac{v/2}{f}. \tag{3}$$

From the fit, $x_0 = 1.974 \pm 0.001$ m, and $v = (2.996 \pm 0.001) \times 10^8$ m/s $= 2.996 \times 10^8$ m/s $\pm 0.03\%$. This value agrees with the speed of light in air 2.997×10^8 m/s at a wavelength of 657 nm. As the measurement involves light pulses, the measured speed should correspond to the group speed of light in air. However, the difference between the group speed and the phase speed of light in air is relatively small, and both speeds are within the error bars of the measured value.

The error bars for position and frequency measurements are too small to be displayed in Fig. 5. Two factors affect the accuracy of the position measurements: Positioning repeatability on the linear stage, which is 0.001 mm, and the alignment of the laser beam along the translational axis of the linear stage. The error in position due to misalignment is estimated to be less than 0.015 mm from the small amount the knobs of the beamsplitter mount need to rotate to make the reflected beam fall back into the laser when the beamsplitter moves between the extremes of the beamsplitter position range. The error in reading the peak frequency of the feedback signal, such as that shown in Fig. 3(b), is 0.002 MHz, which is much larger than the maximum error in measuring the frequency of the oscillator, 0.00032 MHz. The dominant contribution to the error of measuring the speed of light is the error coming from determining the frequency of the peak of the optical back signal, which is much larger than that due to position measurement. For example, using the two extreme data points in Fig. 5 to calculate the speed of light, the contribution to the percent error in speed measurement from position uncertainty, from Eq. (3), is $100 \times (\delta x/\Delta x) = 100 \times (0.015/140) = 0.01\%$, while from the peak frequency uncertainty is $100 \times (2\delta f/\Delta f) = 100 \times (2 \times 0.002/5) = 0.08\%$. From these two extreme points, the speed of light is $v = (2.996 \pm 0.002) \times 10^8$ m/s.

Depending on how much of the setup and alignment is performed in advance, this experiment could be completed during a teaching lab period or built as a longer-term student project. Additional exercises related to the experiment are provided in the supplementary material.[5]

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AUTHOR DECLARATIONS

Conflict of Interest

The author has no conflicts to disclose.

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[5]See the supplementary material at https://www.scitation.org/doi/suppl/10.1119/5.0104758 for the additional exercises related to the experiment.