Time-of-flight measurement of the speed of light using a laser and a low-voltage Pöckels-cell modulator

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An advanced undergraduate laboratory experiment is described which uses a laser, low-voltage pulser, and a Pöckels-cell electro-optical modulator to determine the speed of light using time of flight. Accuracy of about $\frac{1}{2}\%$ is obtained using a calibrated oscilloscope while an uncertainty of less than 0.2% can be obtained using a time-to-analog converter (TAC) and multichannel analyzer (MCA). The experiment is used to illustrate electro-optical modulators and time-of-flight instrumentation.

I. INTRODUCTION

Although the speed of light ("*c*") is now defined[1] in terms of the meter and second, it is still illustrative to have students measure "*c*." The rotating mirror[2] or modulated laser methods[3] are commonly used in lower-level physics laboratories. Advanced student laboratory experiments which measure "*c*" have been described which use pulsed light-emitting diodes,[4] Kerr cells,[5] and other methods. The Kerr-cell method requires a high-voltage pulser and the use of a liquid modulator, usually nitrobenzene. The latter is somewhat dangerous. We have devised a similar experiment which uses a solid-state Pöckels cell[6,7] driven by a low-voltage, fast pulser. A Pöckels cell is an electro-optical crystal, such as ammonium dihydrogen phosphate (ADP), which exhibits birefringence with application of an electric field, i.e., voltage. Pöckels cells are thus widely used as optical modulators of polarized light.[7]

II. SETUP

The experiment is set up in a hallway using the arrangement shown in Fig. 1. The laser Pöckels cell (INRAD Model 102-020), polarizers, beam splitter prism, plane mirror, lenses, and photomultiplier tube (PMT) are mounted on optical benches. The mirror at the end of the hall is on an adjustable telescope mirror mount which can be moved up and down the hall to known distances. An interference filter[8] and blackened cardboard tube are used to minimize light leakage into the PMT. The latter is a fast (rise time <5 ns) 14-stage tube (RCA6810A) obtained as surplus from a nuclear research group. We have used slower tubes (RCA6342A or equivalent) with success. Since the modulation is low, a PMT with low noise is desirable.

The simple lenses (Fig. 1) form a telescope to produce a small, parallel light beam directed down the hall. The reflected beam is then focused back onto the PMT.

The output signals on the PMT anode are observed with a high bandwidth oscilloscope ($bw \geqslant 30$ MHz) having a calibrated time sweep. Alternatively, a time-to-analog converter (TAC), multichannel analyzer (MCA), and standard nuclear instrumentation modules (NIM) have been employed to provide higher accuracy (Fig. 2).

III. PROCEDURE

The laser, optics, and mirror are first aligned without the Pöckels cell and polarizers. The cell, which is on an adjustable mount, is then aligned so that the laser beam is centered on the cell apertures. The polarizers are added and crossed to produce extinction. (The laser output may have an ill-defined polarization. The first polarizer is used to better define the polarization axis.) In practice the polarizers are then adjusted to optimize the observed signals on the PMT.

A fast rise-time voltage pulse is then applied to the Pöckels cell to produce short light pulses, e.g., $t_{rise} \leqslant 10$ ns, width $\leqslant 50$ ns. We have used a standard low-voltage (50 V into 50 Ω) lab pulser for this purpose (HP 214A). A higher voltage pulser would produce greater modulation but we have found the low-voltage pulser to be adequate, particularly if the load resistor value is optimized (Fig. 1). Commercial, fast high-voltage pulsers are available but are relatively expensive (viz. \$1500 to \$2500).[10]

A set of observed PMT anode pulses is shown in Fig. 3. These are typically -30 mV for 1800-V PMT voltage. This is sufficient for direct time-of-flight measurements from

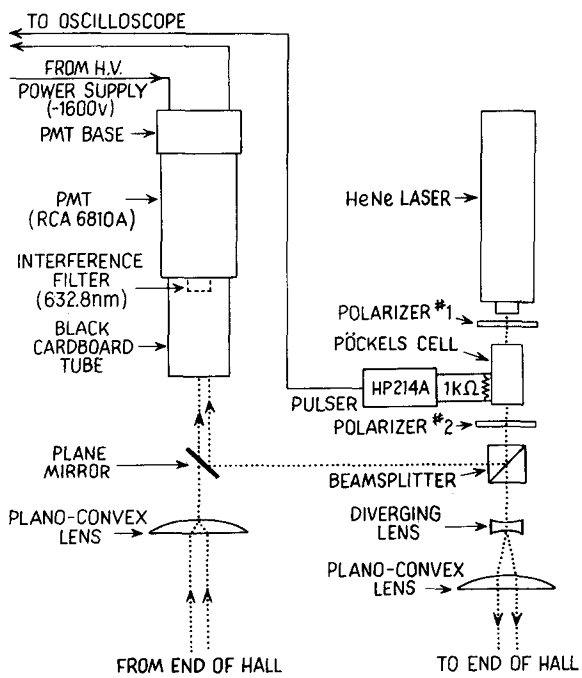

Fig. 1. Experimental setup.

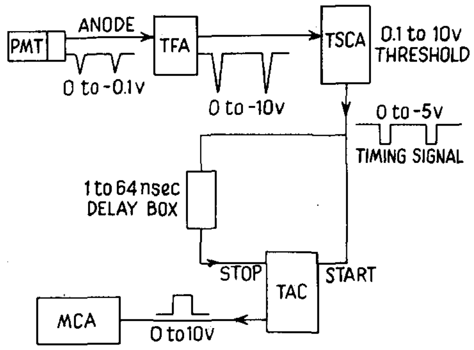

Fig. 2. Time-of-flight instrumentation. TAC: time-to-digital converter (0–400 ns); MCA: multichannel analyzer (0–2048 chs.); PMT: photomultiplier tube; TFA: timing filter amplifier (gain is $\times 100$).

the oscilloscope. A typical set of measurements being

$t = 305 \pm 3$ ns,

$l = 91.436 \pm 0.005$ m,

$c = 2.98 \pm 0.05 \times 10^8$ m/s (in air).

In principle a more accurate value for "c" can be obtained by electronic processing of the PMT signals using standard NIM electronics available in many teaching labs. First, the PMT anode signals are amplified ($\times 10$ to $\times 100$) using a fast voltage or timing filter amplifier (TFA). Timing signals (start and stop) are then generated using a timing single-channel analyzer (TSCA). A variable, known delay can be added to one of the signals to calibrate the TAC and MCA. (In practice the reflected signal is used as the start pulse and a delayed, initial signal is used as a stop pulse, and "c" is obtained from a relative time shift.)

A plot of the resulting TAC spectrum (10 V = 400 ns) as analyzed with a MCA is shown in Fig. 4. Least-squares fitting of the peak centroids yields a time-difference measurement accurate to better than $\pm 0.2\%$. Owing to uncertainties of the propagation delays in the cables, etc., it may be more convenient to measure the shift in TOF when the hall mirror is moved a known distance. Such a measurement[11] is shown in Fig. 5. This yields $c = 2.973 \pm 0.005 \times 10^8$ m/s in air ($n = 1.0003$). (However, since "c" is now defined as 2.99792458 m/s in vacuum, we are actually calibrating our length and time devices.)

IV. CONCLUSIONS

This experiment has been well received by the students, who find it both informative and challenging. It illustrates the use of electro-optical modulators, fast-timing electronics and techniques, as well as more conventional optics (collimation, polarization, beam splitting, filtering, etc.), and is a natural extension of the speed-of-light measurements done in more elementary labs. It also introduces students to TOF instrumentation, which is similar to that used in nuclear and particle physics to detect and measure fast particles, e.g., neutrons. Much of the equipment can be borrowed or obtained from nuclear or particle physics research groups, or is often available on the DOE Energy-Related Laboratory Equipment (ERLE) surplus lists.[12] Otherwise suitable equipment is available commercially

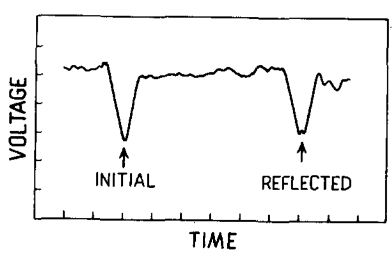

Fig. 3. Oscilloscope trace of transmitted and reflected laser pulses observed at the PMT anode (Fig. 1). One horizontal division equals 50 ns; one vertical division, 10 mV.

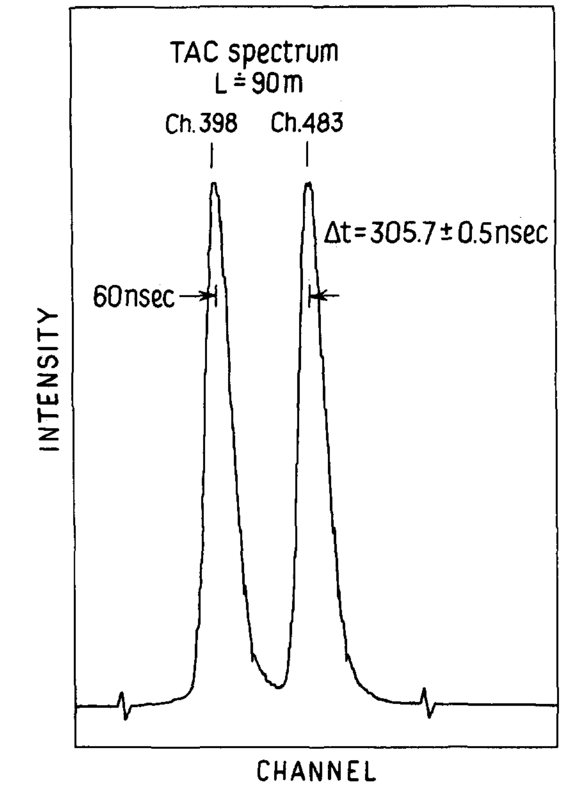

Fig. 4. A TAC spectrum observed in the MCA using the setup shown in Fig. 2. The peaks in channels 398 and 483 are the TOF signals with and without a known (60 ns) time delay added (Fig. 2). This yields a time calibration of 0.7 ns per channel.

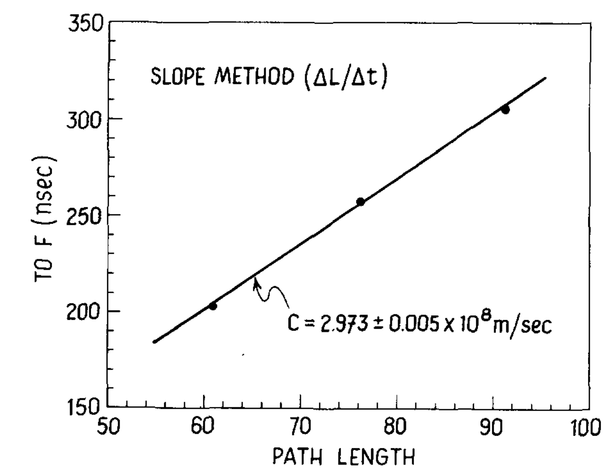

Fig. 5. Time shift versus change in mirror distance (Fig. 1).

(PMT and base ≐ \$300; PMT HV supply ≐ \$600; NIM TAC ≐ \$800; NIM TSCA ≐ \$500; Delay box ≐ \$350; ⩾1-mW He–Ne laser ≐ \$500; ⩾100-MHZ oscilloscope ≐ \$1400). Finally, the Pöckels cell itself is relatively inexpensive (less than \$800) and can be driven by most low-voltage, fast pulsers.

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A note on velocity modulation

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Velocity modulation of an electron beam, which is the underlying physical phenomena for various microwave tubes such as klystrons and magnetrons, is interpreted in terms of a water bag model which has its origin in plasma physics. Using this technique, it is possible to estimate the expected amplitude for a velocity-modulated electron beam.

I. INTRODUCTION

In introductory courses on the physics of high-frequency devices or microwave techniques, one typically describes the concept of velocity modulation of an electron beam as an introduction to the understanding of how klystrons and magnetrons operate. The procedure one usually follows in this introduction is to calculate the kinetic energy that electrons in a beam will gain as they pass through a dc accelerating potential and an ac modulating signal. One can easily show that the velocity of the electrons will consist of a dc part and a sinusoidal ac modulation. Hence, the origin of the name *velocity modulation*. After obtaining this modulated velocity, one typically sketches an Applegate diagram which will show the trajectory in space and time of the electrons that start at various times within the period of the ac modulation after passing through the grid region. Several of these trajectories will intersect at certain locations in space and at discrete times. By placing a second cavity at this "bunched" region, one obtains an amplified response since this localized density perturbation is greater than that of an unbunched beam which is traveling at the same velocity.

The purpose of the present paper is to suggest an alternative approach to illustrate this klystron bunching effect. The approach shall be based on some concepts that originate in plasma physics. The calculation that we present shall follow fairly closely the calculation and the experiment of Ikezi and Folkes,[1] who were able to demonstrate the velocity modulation of an ion beam in phase space with reference to a plasma. We have successfully extended these calculations and experiments to interpret the excitation of linear and nonlinear ion-acoustic waves from a large fine mesh grid inserted in a plasma[2] and the double plasma (DP) method for the excitation of ion-acoustic waves.[3] All three calculations and experiments involved an interpretation using the klystron bunching model. We felt justified, therefore, in reexamining the klystron bunching model itself in terms of this plasma physics type calculation as it may have certain pedagogical advantages. In Sec. II, we present the calculation and Sec. III contains the interpretation and the concluding comments.

II. KLYSTRON BUNCHING

The *modus operandi* of using the plasma physics approach is to employ the fact that the electron particle density can be computed from a distribution function $f(x,v,t)$, where x,v, and t are the position, velocity, and time, respectively. This is effected by integrating the distribution function over all possible velocities. The reader should now ask the question, "How does this distribution function evolve