

Correlation of changes in laser tube temperature, cavity length, and beam polarization for an internal-mirror helium–neon laser

G. A. Woolsey, M. Yusof Sulaiman and Maarof Mokhsin

Citation: [American Journal of Physics](#) **50**, 936 (1982); doi: 10.1119/1.13017

View online: <https://doi.org/10.1119/1.13017>

View Table of Contents: <https://aapt.scitation.org/toc/ajp/50/10>

Published by the [American Association of Physics Teachers](#)

ARTICLES YOU MAY BE INTERESTED IN

[Mode frequency pulling in He–Ne lasers](#)

[American Journal of Physics](#) **67**, 350 (1999); <https://doi.org/10.1119/1.19261>

[A very simple stabilized single-mode He–Ne laser for student laboratories and wave meters](#)

[American Journal of Physics](#) **58**, 878 (1990); <https://doi.org/10.1119/1.16354>

[Polarization of a helium-neon laser](#)

[The Physics Teacher](#) **34**, 346 (1996); <https://doi.org/10.1119/1.2344475>

[Stabilization of a multimode He–Ne laser: A vivid demonstration of thermal feedback](#)

[American Journal of Physics](#) **61**, 932 (1993); <https://doi.org/10.1119/1.17367>

[A simple solution to obtain stabilized linearly polarized light from a randomly polarized He–Ne laser](#)

[American Journal of Physics](#) **59**, 757 (1991); <https://doi.org/10.1119/1.16760>

[Measuring the speed of light using beating longitudinal modes in an open-cavity HeNe laser](#)

[American Journal of Physics](#) **78**, 524 (2010); <https://doi.org/10.1119/1.3299281>



Correlation of changes in laser tube temperature, cavity length, and beam polarization for an internal-mirror helium–neon laser

G. A. Woolsey

Department of Physics, University of New England, Armidale, N. S. W. 2351, Australia

M. Yusof Sulaiman and Maarof Mokhsin

Jabatan Fizik, Universiti Pertanian Malaysia, Serdang, Selangor, Malaysia

(Received 10 August 1981; accepted for publication 20 October 1981)

This experiment involves a study of those changes which occur in an internal-mirror helium–neon laser, during the warm-up period after switch-on. Increase in the tube temperature is measured using an array of thermocouples. Longitudinal expansion of the laser cavity is measured using one or two Michelson interferometers. Switching between axial modes is analyzed by measuring the laser output after transmission through a polarizer. The data from the three sets of measurements are compared by using them to calculate changes in tube length, and good correlation results.

I. INTRODUCTION

Over the years, numerous undergraduate experiments in optics and other fields have been developed using the helium–neon laser, and many of these have been published in the *Journal*. Only recently, however, have papers appeared in which experiments relating to the properties and behavior of the helium–neon laser itself are described. Each of these experiments^{1–3} has dealt with phenomena associated with the simultaneous excitation of several longitudinal or axial modes in an internal-mirror helium–neon laser.

This paper describes an experiment using an internal-mirror helium–neon laser where switching between axial modes is used in the correlation of changes in tube temperature, cavity length, and output polarization.

Most commercially available 0.5- to 2-mW helium–neon lasers used for undergraduate laboratory experiments have internal mirrors and are adjusted to operate in cylindrically symmetric axial modes TEM_{00q} . The frequency of these modes is given by $\nu = qc/2L$, where L is the cavity length and q is an integer.^{4,5} For example, the Spectra-Physics Model 155 helium–neon laser used in the present work has a cavity length of 27.4 cm, and hence a frequency difference, $\Delta\nu$, between adjacent longitudinal modes of 548 MHz. Since the Doppler half-width of the neon 633-nm line is about 1600 MHz, this laser operates simultaneously in two or three axial modes. After such a laser is switched on, there is a period of up to about an hour, during which the temperature of the glass laser tube rises so that the tube slowly expands longitudinally. The cavity therefore lengthens and this causes the axial modes to pass inside the Doppler line of the output. The total output intensity is affected little by this mode switching. If, however, the output beam is passed through a polarizer, then for particular orientations of the polarizer, substantial fluctuations are observed in the intensity transmitted through the polarizer. These fluctuations occur, because successive longitudinal modes are linearly polarized, with alternate modes following two perpendicular directions π and σ .

Tang and Statz⁶ have shown that when a gas is irradiated by two oscillating linearly polarized fields of different frequencies well within the Doppler-broadened width of the same absorption line, maximum absorption of both fields occurs when the two linear polarizations are perpendicular to each other. Consequently, when a gas laser oscillates simultaneously in two or more longitudinal modes, oscilla-

tions in adjacent modes corresponding to orthogonal linear polarizations (π and σ) are built up most rapidly and ultimately prevail.

If the polarizer is placed in the path of the laser beam with its transmission axis parallel to one of the directions of polarization (π and σ), the passage of the modes within the Doppler line can cause intensity fluctuations as high as 40% of the mean intensity. The intensity of the Spectra-Physics Model 155 laser transmitted through a polarizer orientated in this manner is shown as a function of time in Fig. 1, together with a series of schematic diagrams which illustrate how these intensity variations may be correlated with changes in mode structure within the Doppler line. At an intensity maximum, the laser output is dominated by an axial mode that is polarized in the direction of the transmission axis of the polarizer, say the π direction, and at a minimum, by an axial mode polarized in the orthogonal direction, σ . Intensities between maxima and minima correspond to different combinations of π and σ modes. A

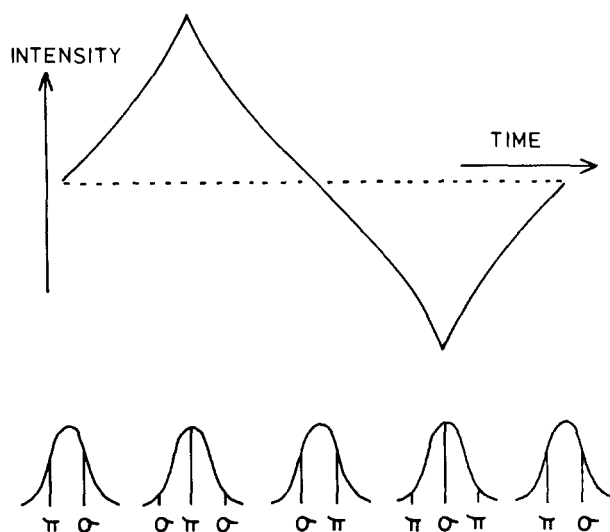


Fig. 1. Intensity of a Spectra-Physics Model 155 helium–neon laser, after transmission through a polarizer, as a function of time during warm-up, for one cycle of axial mode changes—the transmission axis of the polarizer is parallel to the π direction of polarization of the laser output. The mode structure within the Doppler line is shown at various stages of the cycle of axial mode changes.

change from a maximum to the adjacent minimum in intensity corresponds to a switch from one mode to the next and hence to a change in cavity length of $\lambda/2$, where $\lambda = 633$ nm.

This movement of modes inside the Doppler width of the laser line represents an instability which must be eliminated if the laser is to be used for precision length measurement, and several methods⁷⁻⁹ have been devised to stabilize internal-mirror helium-neon lasers.

The output of an internal-mirror helium-neon laser can be polarized by placing a permanent magnet around the laser cavity so that a magnetic field exists perpendicular to the axis of the cavity. The magnetic field causes the laser energy to be concentrated into the π modes.^{9,10} An investigation of the outputs of several magnetically polarized helium-neon lasers, of the type found in teaching laboratories, has recently been reported in the Journal.¹¹ The results suggest that fluctuations in polarization of the output from such lasers can still be significant enough to cause problems in experiments illustrating effects which depend on polarization.

In the present experiment, each of the quantities, laser beam polarization, cavity length, and discharge tube temperature, are measured independently for an unpolarized, internal-mirror, helium-neon laser. The results of the three sets of measurements are correlated to show their interdependence.

II. EXPERIMENTS

The tube of the Spectra-Physics Model 155 helium-neon laser has internal mirrors, a cavity of diameter 1.5 mm and length 27.4 cm, and a discharge length of 10.0 cm, which is at one end of the cavity. For this study, the tube system was removed from its box and supported horizontally by a clamp around the cathode side arm which runs parallel to the laser tube. An experimental study was made of changes in the length of the cavity, the tube temperature, and the laser output at 633 nm, during tube warm-up. The laser tube and measuring systems were placed on an optical table fitted with pneumatic vibration isolators and arranged as shown in Fig. 2.

The output of the laser tube was transmitted through a polarizer to a photodetector, and the output of the photodetector fed to an $x-t$ chart recorder. With the polarizer

suitably orientated, the polarization of the laser output can be examined as described in Sec. I.

The linear expansion of the laser cavity is monitored by measuring the change in position of each of the end mirrors. This is done by using a laser end-mirror as one mirror of a Michelson interferometer.¹² A separate helium-neon laser is used as light source for the interferometer, and the resultant fringes, after expansion by a 10-cm focal length lens, can be viewed on a screen and counted visually as the laser end-mirror moves. Alternatively, fringe movement can be monitored using an aperture and photodetector as shown in Fig. 2, with the output of the photodetector displayed on an $x-t$ chart recorder. In making the interferometer measurements, care must be taken to eliminate any fringe movement due to mode switching and instabilities in the interferometer laser source when this is an internal-mirror device. This can be done by keeping the two arm lengths of the Michelson interferometer closely the same, and by switching on the interferometer laser source 20–30 min before starting measurements.

The three sets of optical measurements, one of the laser output and two of the movement of the laser end-mirrors, can be made simultaneously as shown in Fig. 2. The laser output beam is then monitored, using polarizer and detector, after reflection from the compensating glass plate of an interferometer, as shown in Fig. 2. We experienced no difficulty in isolating the reflected laser output beam from the reflected interferometer beam. On the other hand, the three sets of measurements can be made separately, so that only one interferometer is then needed. Repeatability is good enough to allow each set of measurements to be made during separate laser warm-up periods, provided of course that the laser tube is allowed to come to room temperature between sets of measurements.

The temperature of the laser tube was monitored along its length, during the warm-up period, using an array of chromel–alumel thermocouples. Eleven thermocouples were placed at different positions along the tube as shown in Fig. 2, with a concentration on the discharge region, where the largest temperature changes occur. The thermocouples were constructed from 0.2-mm diameter wires. They were held in contact with the outer glass wall of the laser cavity and insulated from the surrounding air, using Torr-seal.¹³ The output of each thermocouple can be measured as a function of time using an $x-t$ chart recorder. The

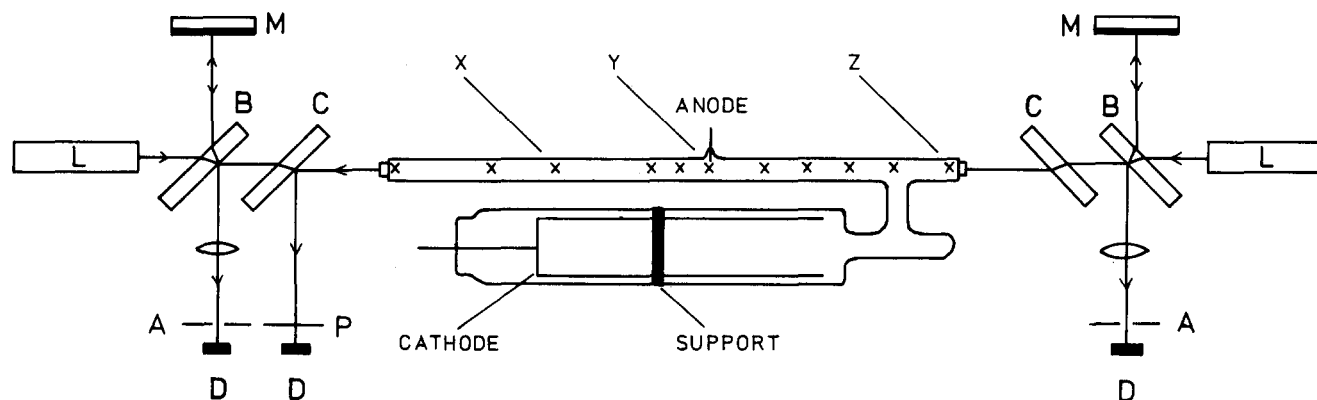


Fig. 2. Laser tube and measuring systems, including two Michelson interferometers. The thermocouple positions are indicated on the tube with X, Y, and Z referring to Fig. 4. L—laser sources for interferometers. M—interferometer mirrors. B—interferometer beam splitters. C—interferometer compensating plates. A—apertures. P—polarizer. D—detectors.

most important measurements, however, are the equilibrium temperatures reached when the laser tube has been switched on for some time. These measurements of equilibrium temperatures can be made for each thermocouple, in turn, using a reference thermocouple at 0 °C and a micro-voltmeter.

III. RESULTS AND DISCUSSION

A. Optical data

As examples of the results obtained using the optical techniques, data from the first 5 min of the warm-up period of the Model 155 laser tube are displayed in Fig. 3 on the same time scale. These data were obtained during successive warm-up periods, the laser tube being allowed to cool to room temperature between each set of measurements. The total time involved in making all the measurements in Fig. 3 was about 1 h.

The shape of the curve, Fig. 3(a), for laser output, after passing through the polarizer, is typical of such curves, and shows how the rate of mode switching falls off with time as the tube expansion rate decreases. Comparison of the interferometer fringe traces for the laser end-mirrors, Figs. 3(b) and 3(c), shows that the mirror at the discharge end of the laser tube moves outward less rapidly than the mirror at the other end. This is because the laser tube arrangement was fixed to the optical table by a clamp around the cathode side-arm tube, and this side arm is joined to the laser cavity tube near the discharge end as seen in Fig. 2. Consequently, the discharge end of the laser tube is held in position more

rigidly than the other end. We made some efforts to clamp the laser tube rigidly at one end and hence fix one end-mirror, so that an interferometer study of only one end-mirror would be needed. We were unable, however, to eliminate mirror movement completely for the clamped end.

Each single fringe movement in Figs. 3(b) and 3(c) corresponds to a mirror movement of one half-wavelength ($\lambda/2$). The increase in length of the laser cavity at any time is given therefore by the sum of the fringe shifts for the two end-mirrors times $\lambda/2$. Since each longitudinal mode switch of the laser occurs with a cavity length change of $\lambda/2$, the fringe-shift sum should equal the number of mode switches, corresponding to the number of maxima and minima in Fig. 3(a).

The agreement between Fig. 3(a), on the one hand, and Figs. 3(b) and 3(c), on the other, is good, with Fig. 3(a) indicating 48 mode switches and Figs. 3(b) and 3(c) indicating a fringe movement totaling 49. The small discrepancy is due to the data being obtained during successive warm-up periods, and exact agreement is obtained when simultaneous measurements are made. After 15-min warm-up, the time between mode switches has increased to several minutes, and tube expansion is negligible after about 1 h.

For correlation with the thermal data, the increase in length of the laser tube, after a warm-up period of 30 min, was calculated from the mode-switching data. With the laser tube initially at 25 °C, 72 mode switches occur in that period, corresponding to an increase in length of 36λ or 2.28×10^{-5} m.

B. Thermal data

Figure 4 shows how the temperature of the outer wall of the laser tube increases with time for three positions along the length of the tube.

Figure 5 shows a wall temperature profile along the length of the tube, after the laser has been running for 30 min at a room temperature of 25 °C. This profile gives a mean wall temperature of 48.5 °C, corresponding to a rise

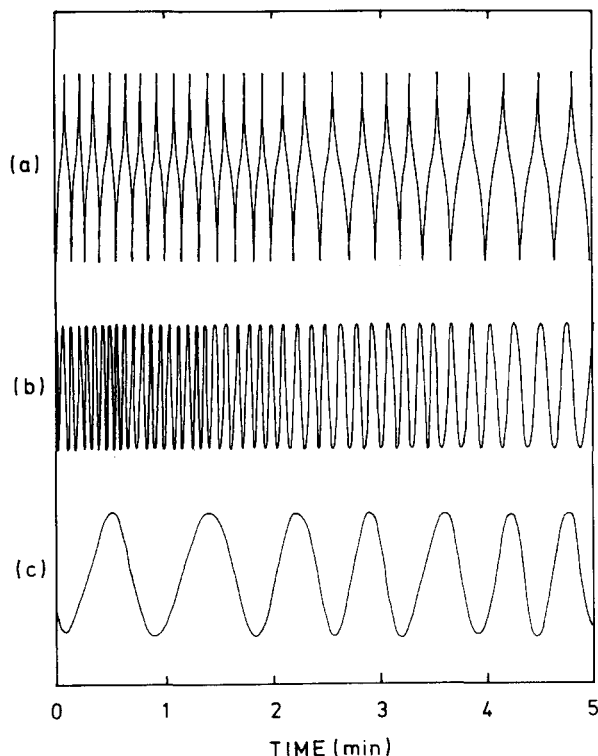


Fig. 3. Optical data for the first 5 min of laser tube warm-up obtained using the measuring systems of Fig. 2. (a) Laser output transmitted through polarizer, with transmission axis parallel to one of the directions of polarization of the laser output. (b) Interferometer fringe trace for the laser end-mirror at the nondischarge end (left-hand end in Fig. 2). (c) Interferometer fringe trace for the laser end-mirror at the discharge end (right-hand end in Fig. 2).

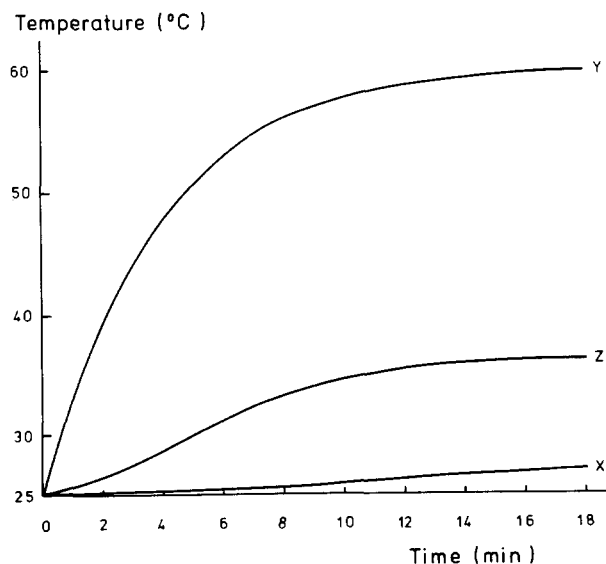


Fig. 4. Temperature-time curves for the outer wall of the laser tube during warm-up for an initial temperature of 25 °C. The curves were obtained using chromel-alumel thermocouples placed at the positions X, Y, and Z shown in Fig. 2.

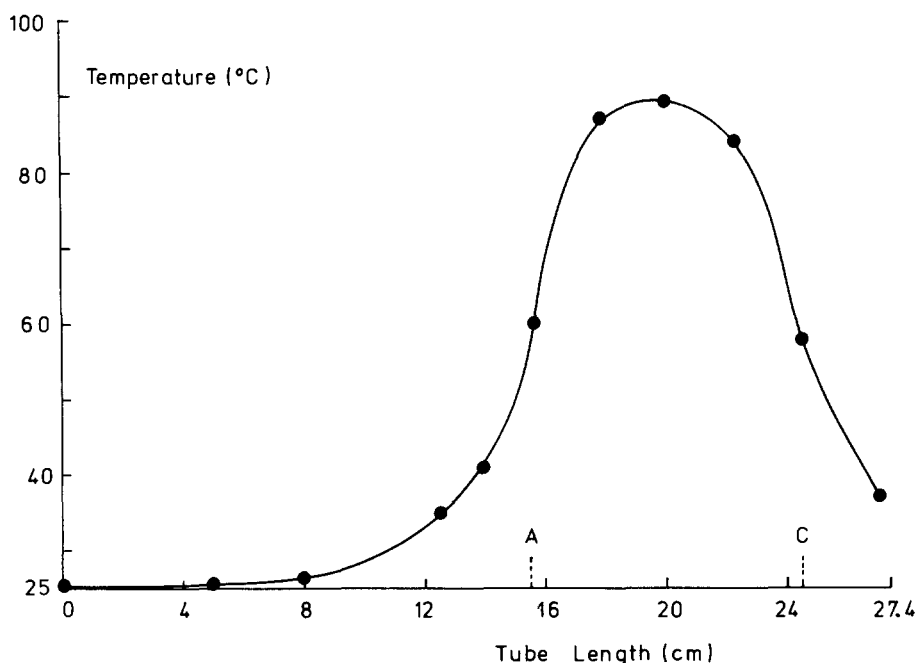


Fig. 5. Temperature of the outer wall of the laser tube along the tube length, after a warm-up period of 30 min. The tube was initially at a temperature of 25 °C. The positions of the anode (A) and cathode side arm (C) are as shown.

in mean wall temperature of 23.5 °C.

The increase in tube length at any time during warm-up is given by $L\alpha\Delta T$, where L is the tube length at room temperature, α is the thermal expansion coefficient, and ΔT is the increase in mean tube temperature.

The following analysis shows that at any time after a warm-up period of 15 min, the experimentally determined mean outer wall temperature is close enough to the mean temperature of the tube as a whole that the wall value can be used in the calculation of tube expansion.

It is clear from the temperature-time curves of Fig. 4 that the temperature distribution throughout the laser tube is close to steady state after a warm-up period of about 15 min. The only variation after this time is a small increase near the end of the tube furthest from the discharge region. This conclusion is supported by the optical measurements which show that 95% of the tube expansion due to the warming-up process occurs in the first 15 min.

This being the case, an expression for the radial temperature distribution $T(r)$ through the tube wall at any position along the tube length can be obtained by solving the steady-state heat-conduction equation

$$\frac{\partial^2 T(r)}{\partial r^2} = 0, \quad \text{with } Q(r_i) = -k \left(\frac{\partial T}{\partial r} \right)_{r=r_i} 2\pi r_i,$$

where $Q(r_i)$ is the rate at which heat is supplied per unit length at the inner wall of radius r_i , and k is the thermal conductivity of the glass wall.

Solution of this equation leads to an expression for the radial temperature distribution:

$$T(r) = T_0 + [Q(r_i)/2\pi k] \ln(r_0/r), \quad (1)$$

where T_0 is the temperature at the outer wall of radius r_0 .

Equation (1) can be used to obtain an expression for the temperature $T(r_m)$ at the mean wall radius, r_m

$$T(r_m) = T_0 + \frac{Q(r_i)}{2\pi k} \left[1 - \frac{r_i}{(r_0 - r_i)} \ln \left(\frac{r_0}{r_i} \right) \right]. \quad (2)$$

We are interested in obtaining a mean value for $T(r_m)$ along the length of the tube, and this can be done by using a

mean value for $Q(r_i)$ in Eq. (2). The total power input at the inner wall is VI , where V is the voltage drop along the 10 cm length of discharge column within the laser tube, and I is the discharge current. The mean value of Q over the entire tube length L can therefore be written as VI/L . Equation (2) is then rewritten to provide an expression for the increase in mean temperature of the laser tube, under steady-state conditions, as

$$T_{av}(r_m) - T_0 = \frac{VI}{2\pi kL} \left[1 - \frac{r_i}{(r_0 - r_i)} \ln \left(\frac{r_0}{r_i} \right) \right]. \quad (3)$$

The current I flowing in the laser discharge is 6.8 mA, and V can be estimated from the total discharge voltage which is 850 V. Allowing for a drop of 150 V across the cathode fall¹⁴ of the discharge, this leaves 700 V across the total column length, which extends over a 5 cm length of side arm, as well as the 10 cm length of laser tube. Assuming the electric field in the column to be uniform,¹⁴ the voltage drop V across the 10 cm length of column in the laser tube will be 470 V. $[T_{av}(r_m) - T_0]$ is then evaluated from Eq. (3) using these values of V and I , together with $L = 27.4$ cm, $r_0 = 5.5$ mm, $r_i = 0.75$ mm, and a value for k of $1.17 \text{ W m}^{-1} \text{ K}^{-1}$ which is the value for Corning 7740 borosilicate glass (Pyrex).^{15,16} The value obtained for this temperature difference is 1 °C. Consequently, for any time after the laser has been running for 15 min, the error introduced into the $L\alpha\Delta T$ calculation of the length increase, by taking ΔT as the increase in mean wall temperature, turns out to be less than 5%. For example, the value of 23.5 °C obtained from Fig. 5 can be used as ΔT to calculate the increase in tube length, after a warm-up period of 30 min. With this ΔT value, $L = 27.4$ cm, and $\alpha = 3.3 \times 10^{-6} \text{ K}^{-1}$, which is the thermal expansion coefficient for Corning 7740 borosilicate glass (Pyrex),^{15,16} the increase in length is 2.12×10^{-5} m. The agreement with the value of 2.28×10^{-5} m calculated from optical data is good. As would be expected, the agreement is improved by using a ΔT value of 24.5 °C, which according to our radial heat conduction analysis, should be closer to the increase in mean tube temperature:

the increase in length calculated from the thermal data is then 2.22×10^{-5} m.

IV. SUMMARY AND CONCLUSIONS

The increase in length of an internal-mirror helium–neon laser tube during its warm-up period has been studied using three different experimental techniques: two optical and one thermal. The agreement is good between the results determined by the three techniques. The optical measurement techniques provide a continuous assessment of the change in tube length. The thermal technique on the other hand relies on measurements made when the temperature distribution through the laser tube is close to steady state, and this occurs after the laser has been running for about 15 min.

The experiment brings together a number of physical principles and experimental techniques in the areas of optics and heat. It provides an opportunity to study the fundamental behavior of a helium–neon laser, in contrast to making use of the laser as a measurement tool. Most important is that the diverse experimental methods used provide reliable and precise data, which correlate in a most satisfying manner. On the other hand, the equipment required is not complex and is likely to be available from other experiments in the undergraduate laboratory.

We have found that the experiment is an appropriate one for either the second or third year undergraduate laboratory. Although the detailed theory of polarization and mode switching in the helium–neon laser is not normally covered at the second year level, we find that our better second year students are able to appreciate the basic concepts underlying the experiment.

ACKNOWLEDGMENT

We wish to acknowledge the assistance provided for this project by the Australian–Asian Universities' Cooperation Scheme.

- ¹R. G. Brickner, L. A. Kappers, and F. P. Lipshultz, *Am. J. Phys.* **47**, 1086 (1979).
- ²C. Wong, T. Webb, and C. Londono, *Am. J. Phys.* **48**, 306 (1980).
- ³P. A. Casabella, T. Gonsiorowski, and A. Leitner, *Am. J. Phys.* **48**, 393 (1980).
- ⁴A. E. Siegman, *An Introduction to Lasers and Masers* (McGraw–Hill, New York, 1971), pp. 332–335.
- ⁵C. Roychoudhuri and R. H. Noble, *Am. J. Phys.* **43**, 1057 (1975).
- ⁶C. L. Tang and H. Statz, *Phys. Rev.* **128**, 1013 (1962).
- ⁷R. Balhorn, H. Kunzmann, and F. Lebowsky, *Appl. Opt.* **11**, 742 (1972).
- ⁸S. K. Gordon and S. F. Jacobs, *Appl. Opt.* **13**, 231 (1974).
- ⁹G. Mas, H. Blancher, and J. Roig, *Appl. Opt.* **13**, 2771 (1974).
- ¹⁰R. A. J. Keijser, *Opt. Commun.* **23**, 194 (1977).
- ¹¹E. Fortin and D. Singh, *Am. J. Phys.* **49**, 891 (1981).
- ¹²We used Ealing Universal Interferometers, available from Ealing Beck Ltd., Watford, England.
- ¹³Varian Associates, Vacuum Division, Palo Alto, CA.
- ¹⁴A. von Engel, *Ionised Gases*, 2nd ed. (Oxford University, London, 1965), Chap. 8.
- ¹⁵*CRC Handbook—Appl. Eng. Sci.*, 2nd ed., edited by R. E. Bolz and G. L. Tuve (Chemical Rubber Company, Boca Raton, FL, 1973), Sec. 1.4.
- ¹⁶We were unable to determine from the manufacturer, the type of glass used for our Model 155 laser; but measurements of annealing point and density made on another broken Model 155 tube, suggest that it is Corning 7740 (Pyrex).

Generation of simple harmonic motions

C. C. Yan

Instituto de Física, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brazil

(Received 17 August 1981; accepted for publication 11 November 1981)

Simple harmonic motion is examined from the viewpoint of how such motion can be generated. It is shown that a family of plane curves including circles as its subfamily generate simple harmonic motions by projection. The idea of dynamic force constants is introduced. Employing such an idea, one may conclude that any force field that generates a simple harmonic motion is equivalent to the force field obeying Hooke's law with the force constant replaced by the appropriately generalized dynamic force constant.

I. INTRODUCTION

Simple harmonic motion is one of the most discussed subjects in physics. The equations that describe such motions are very simple, being linear differential equations of second order with constant coefficients. One may note that the simple harmonic motion introduced through such equations possesses the following characteristics: (a) The angular frequency is determined by intrinsic physical para-

meters such as force constant and mass of the particle and is not a function of the state of the motion or energy of the system. (b) The amplitude is proportional to the square root of the energy of the moving particle. However, using of differential equations is not the only way to introduce simple harmonic motion. In fact, when the subject is first introduced to beginners without the background of differential equations, it is through the use of projecting the motion of a particle, moving at a constant speed along a circle, onto the