[12] S. S. Todd and R. E. Lorenson, "Heat capacities at low temperatures and entropies at 298.16 K of metatitanates of barium and strontium," J. Am. Chem. Soc. **74**, 2043–2045 (1952).

[13] The standard error represents a $\pm 1\sigma$ interval, so that in case of a Gaussian distribution the true value has about 68% probability of lying between $x-\sigma$ and $x+\sigma$.

[14] K. R. Popper, *The Logic of Scientific Discovery* [Hutchinson, London, 1959 (German first edition 1934)], Chap. 9.

Stabilization of a multimode He–Ne laser: A vivid demonstration of thermal feedback

Ferdinand Stanek,[a)] R. G. Tobin,[b)] and C. L. Foiles
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824-1116

(Received 9 November 1992; accepted 10 March 1993)

A thermal stabilization technique for multimode He–Ne laser tubes is demonstrated. Intensity stability of ~1% is achieved, where the intensity of the unstabilized laser varied by more than a factor of 5. The system provides both a dramatic demonstration of the principle of negative feedback and a stimulating introduction to basic electronics, laser physics, and solid state physics. It is simple enough to be constructed as an undergraduate laboratory project.

I. INTRODUCTION

Inexpensive He–Ne lasers often exhibit very large intensity fluctuations, which result from mode switching and persist for many hours after the laser is turned on. Although rapid sampling or modulation techniques can be used to overcome these fluctuations, they are a serious hindrance to many experiments that depend on measurement of laser intensity. Stahlberg *et al.*[1] have shown that a thermal feedback technique can effectively stabilize single-mode He–Ne laser tubes. Here we show that the same technique can be applied to multimode tubes, and provides a dramatic example of the effectiveness of negative feedback. The system is inexpensive (under $200)[2] and simple to construct, yet a full understanding of its operation requires mastery of important concepts from electronics, laser physics, and solid state physics. Stabilization of a laser by this method can be an excellent and exciting undergraduate laboratory project. In addition, the stabilized laser exhibits fractional intensity variations on the order of 1%, making it suitable for many optical experiments.

II. THEORY OF OPERATION

A thorough discussion is given in Ref. 1; here we provide only a brief summary. The longitudinal mode frequencies of an internal mirror laser of cavity length L are given by

$$\nu_m = m(c/2L), \tag{1}$$

where m is an integer and c is the speed of light. The spacing between adjacent modes is therefore $c/2L$. The effective gain profile of the He–Ne plasma depends upon the gas temperature and degree of population inversion;[3] a spectral width of 1.5 GHz is typical.[1] Depending on the length of the cavity, one or more longitudinal modes may have sufficient gain to oscillate.[3] As the tube heats up, its length L increases, causing the longitudinal modes to sweep through the gain profile.[4] For the free-running laser, these mode switches produce large intensity fluctuations.

The thermal feedback loop stabilizes the temperature of the tube (and therefore L) by coupling the current through a heater to the light output of the laser. A simple proportional feedback system is used, in which the heater current is proportional to the difference between the detector output and a stable set-point voltage. We operate in a regime in which an increase in laser temperature results in a decrease in light intensity.

III. APPARATUS

A schematic diagram of the system is shown in Fig. 1. The laser is a surplus 1 mW He–Ne laser (Spectra Physics Model 88)[5] from a supermarket checkout scanner. The cavity length L is 24.1 cm, giving a longitudinal mode spacing of 622 MHz. Assuming a nominal gain profile width of 1.5 GHz, we expect this tube to support two to three modes. The 2.5-mm-diam beam passes through a pinhole of slightly larger diameter, which blocks incoherent plasma emission from reaching the detector. The most dramatic effects are achieved when a polarizer is placed in the beam. Its orientation is selected to give the best performance; we assume this orientation is parallel to that of one of the lasing modes. A beam splitter directs a fraction of the intensity to the detector. Good results were obtained with as little as 2% of the main beam; a microscope slide also makes an adequate beam splitter. (Our laser did not provide a back beam; if one is available, no beam splitter is needed.)

Our detector is an inexpensive commercial photoconductor with a 3.0×4.2 mm active area and a resistance under operating conditions of 400–4000 Ω. It is important that the sensing area be larger than the laser beam to avoid spurious signals from slight beam movements. The photoconductor was current biased (−3.2 mA) by op-amp A1 (both A1 and A2 were ordinary model 741 op amps); the polarity of the bias current was chosen to give the correct

© 1993 American Association of Physics Teachers

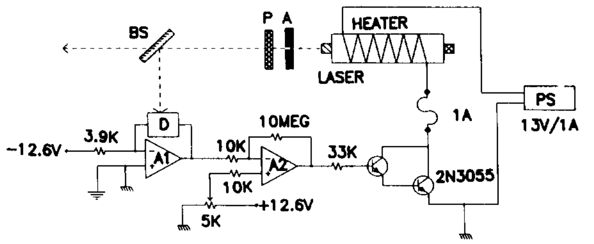

Fig. 1. Schematic diagram of stabilized laser system. A: pinhole aperture, P: polarizer, BS: beam splitter, D: detector, PS: power supply. A ±15 V power supply for the op amps is also required, but is not shown.

sign of feedback. The voltage at the output of A1 is positive and proportional to the resistance of the detector, and therefore inversely related to the light intensity.

The detector was calibrated by comparison with a laser power meter. At the bias currents and laser powers used in our experiment, the I–V characteristic was linear, and the resistance of the detector R_D displayed a power-law dependence on laser intensity I_L with an exponent of -0.63:

$$R_D \propto I_L^{-0.63}. \tag{2}$$

Op-amp A2 compares the detector voltage to a stable set-point voltage selected by the 5 kΩ, 10-turn potentiometer; this voltage selects the operating point of the laser. Since the intensity of the stabilized laser must be lower than the maximum intensity of the free-running laser, the set-point voltage must be greater than the minimum detector signal obtained without feedback. For maximum stability, both the detector bias current and the set-point voltage are derived from mercury batteries. The voltage is amplified by -1000 and used to drive the two transistors, which are connected as a Darlington pair.

The two transistors, together with the 33 kΩ resistor, constitute a voltage to current converter, and control the current through the heater. Since the heater current can be as much as 1 A, the second transistor must be a power transistor and mounted on a heat sink; the 2N3055 used is rated at 15 A and 115 W. The first transistor can be any general purpose *NPN* transistor. The heater is a thin, flexible thermofoil (Minco, Inc. Model HN5507)[5] tightly bound to the center of the laser tube with an acrylic shrink wrap. The heater is driven by an independent power supply capable of providing 1 A at 15 V. It is important that the negative side of the supply be connected directly to the emitter of the power transistor, as shown, so that the large heater current does not introduce spurious voltages in other parts of the circuit. The best stability was achieved when the circuit common was connected to earth ground at a single point, as indicated in Fig. 1.

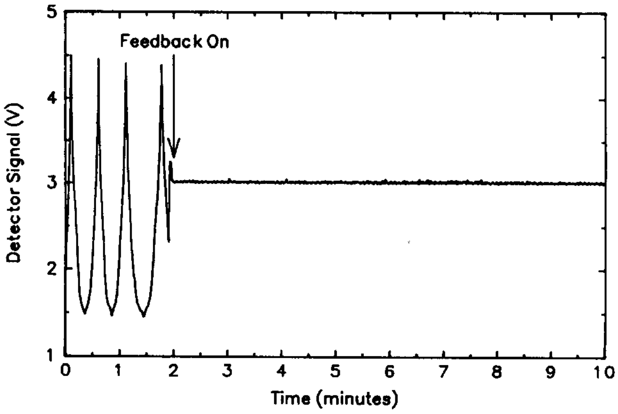

Fig. 2. Stabilization of laser intensity with polarizer in beam. The detector signal is inversely related to the laser intensity. The signal variations in the first 2 min correspond to changes in laser intensity by a factor of 5. After stabilization the fractional intensity variation drops to ~1.4%.

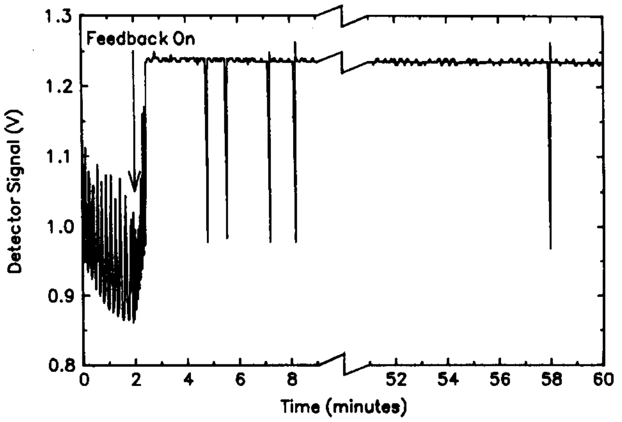

Fig. 3. Stabilization of unpolarized laser intensity. After stabilization the fractional intensity variation is ~0.4% over periods of several minutes, but intermittent large spikes remain.

Other types of detector, laser, and heater could certainly be used; our system, for example, was also operated successfully with a Newport Research Model 820 laser power meter.[5] Minor modifications may then be necessary to maintain negative feedback and avoid oscillations. If the detector used has a high output impedance (like our laser power meter) a unity gain buffer may be necessary.

IV. PERFORMANCE

Figures 2 and 3 show typical examples of the performance of the system. The quantity plotted is the detector voltage measured at the output of A1; this voltage is inversely related to the laser power. For Fig. 2, a polarizer was placed in the beam and rotated to give the largest intensity fluctuations with the feedback circuit off. The extreme instability of the free-running laser is apparent; the laser intensity varied by nearly a factor of 6 over less than 1 min. After approximately 2 min, the feedback system was activated by turning on the heater power supply. After several seconds (related to the thermal time constant of the heater and laser tube), the detector output stabilized at the set point and remained constant for several hours. The rms fractional variation of the detector voltage was 0.9%, corresponding to 1.4% variation in the laser intensity.

In Fig. 3, no polarizer was used. The fluctuations of the free-running laser were less dramatic, but still very large. When the feedback circuit was turned on, the signal stabilized within about 1 min, and the rms fractional voltage fluctuations, neglecting the infrequent spikes, were at the 0.25% level, corresponding to 0.4% intensity fluctuations. However, we were not able to eliminate the occasional large spikes (momentary increases in laser power) apparent in Fig. 3. They did become less frequent with time;

after a half-hour of stabilized operation the time between spikes was 10–20 min. The spikes presumably arise from mode hops.

The intensity stability achieved is somewhat inferior to the 0.1% reported by Stahlberg *et al.*[1] for a single-mode tube. The difference may arise from the much larger mass of the multimode tube used here, which limits the response time of the thermal feedback, or it may be a result of competition between different longitudinal modes.

V. SUMMARY

We have demonstrated the stabilization of an inexpensive multimode He–Ne laser by means of thermal feedback, using the method of Stahlberg *et al.*[1] When the feedback is turned on, intensity fluctuations—which can be nearly a factor of 6 for the free-running laser—are reduced to $\sim 1\%$ in less than 1 min, and the intensity can be held stable for periods of hours. In addition to providing a stable light source for optics experiments, this project provides an extremely vivid demonstration of the power of negative feedback, and a thought-provoking introduction into aspects of laser physics, electronics, and solid state physics. The technique is simple enough, and the equipment inexpensive enough, for an undergraduate laboratory project. In fact, one of us (F.S.) developed this system while an undergraduate, and it is now being used as a demonstration in an optics laboratory course.

---

[a] Current address: Dept. of Electrical Engineering and Electrophysics, University of Southern California, University Park, Los Angeles, California 90089.

[b] To whom correspondence should be addressed.

[1] B. Stahlberg, P. Jungner, and T. Fellman, "A very simple stabilized single-mode He–Ne laser for student laboratories and wave meters," Am. J. Phys. **58**, 878–881 (1990).

[2] This price, in 1992 dollars, includes the laser, detector heater, and electronic components, but does not include the power supplies.

[3] A Yariv, *Quantum Electronics* (Wiley, New York, 1975), pp. 256–258.

[4] G. A. Woolsey, M. Y. Sulaiman, and M. Mokhsin, "Correlation of changes in laser tube temperature, cavity length, and beam polarization for an internal-mirror helium–neon laser," Am. J. Phys. **50**, 936–940 (1982).

[5] Reference to vendor names is for technical information only, and does not imply recommendation, or that other units would not be suitable.

THEORY-LOADED PHYSICS

The old physics was common-sense physics. Experimenters began by mapping out large cross-section processes and then examined them in detail. The new physics was theory-loaded. Experimenters sought to isolate and explore the rare, small cross-section processes of particular significance in the gauge-theory world-view.

Andrew Pickering, *Constructing Quarks—A Sociological History of Particle Physics* (University of Chicago, Chicago, 1984), p. 353.

COMPLACENCY AND HUMILITY

The history of animal behaviour—in particular the sterility of the older experimental approach—illustrates the danger of doing experiments in the Baconian style; that is to say, the danger of contriving 'experiences' intended merely to enlarge our general store of empirical knowledge rather than to sustain or confute a specific hypothesis or presupposition. The history of embryology shows the dangers of an imagined self-sufficiency, for embryology is an inviable fragment of knowledge without genetics. (I often wonder what academics mean when they say of a certain subject that it is a 'discipline in its own right;' for what science is entire of itself?) You may think our recent history entitles us to feel pretty pleased with ourselves. Perhaps: but then we felt pretty pleased with ourselves twenty-five years ago, and in twenty-five years' time people will look back on us and wonder at our obtuseness. However, if complacency is to be deplored, so also is humility. Humility is not a state of mind conducive to the advancement of learning. No one formula will satisfy that purpose, for there is no one kind of scientist; but a certain mixture of confidence and restless dissatisfaction will be an ingredient of most formulae. Confident we may surely be, for the next twenty-five years will throw up many new ideas as profound and astonishing as any I have yet described.

Peter Medawar, *Pluto's Republic* (Oxford, New York, 1984), p. 297.