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R. E. Robert

Daniel J. Jones

Kaare J. Nygaard
Missouri University of Science and Technology

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Robert E. Hebner, Jr.; J. Daniel Jones; Kaare J. Nygaard

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GaAs Laser Experiments for the Undergraduate Laboratory*

ROBERT E. HEBNER, JR.†
J. DANIEL JONES
KAARE J. NYGAARD
Department of Physics
University of Missouri—Rolla
Rolla, Missouri 65401
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A set of laboratory experiments designed to investigate the properties of gallium arsenide lasers is reported. GaAs laser experiments are well suited for undergraduate laboratory because they provide an opportunity to study the physics of electro-optical devices for a minimum capital investment. The specific experiments presented in this paper describe the determination of the current necessary for "lasing" to occur, an investigation of the variation of the wavelength of the emitted light as a function of the laser temperature, and a study of the polarization of the emitted light. All of the experiments presented have been used in an advanced undergraduate laboratory.

INTRODUCTION

A recent article in this Journal enumerated the pedagogical advantages of an undergraduate laboratory investigation of light emitting diodes and outlined some specific experiments.[1] The purpose of this paper is to report on GaAs laser experiments performed by undergraduate students during the past two years.

The GaAs laser experiments are well suited for undergraduate investigations for a variety of reasons. They can be set up for a minimum capital investment: the lasers themselves cost less than $25. They offer an opportunity to study the physics of electro-optical devices, which are predicted to become increasingly important to the physics community.[2] Finally, the student can pursue his study in a variety of directions, depending on his background and temperament.

A GaAs laser is a semiconductor diode laser. In its simplest form it consists of a *p-n* junction that is activated by injecting electrons into the conduction band.[3] The subsequent recombination of electrons and holes leads to the emission of radiation whose frequencies correspond approximately to the energy difference between the conduction and valence bands of the semiconductor material. The lasers are operated as diodes with constant or pulsed currents. Most cw lasers are operated in the vicinity of 77°K, although double-heterostructure lasers have been operated continuously at room temperature.[4] The energy gap between the valence and conduction bands is controlled by doping of the material,[5] by temperature,[6] by an applied magnetic field,[7] and even to a small extent by pressure,[8] resulting in output wavelengths in the range from 6300–9100 Å. When the current through the junction exceeds a certain threshold, the emitted spectrum consists of a series of equally spaced, very sharp lines. On the other hand, for rates of injection below the threshold current a wide recombination spectrum is emitted. Because of the small effective volume and aperture of the *p-n* junction, the radiation pattern is diffraction limited, with a beam divergence of about 20° in a direction perpendicular to the junction plane. Furthermore, the radiation is polarized with vector **E** perpendicular to the junction plane,[9] although modes with **E** parallel to the plane have also been observed.[10]

THEORY

The discussion included in this section is intended only to aid the reader in understanding the remainder of the paper. Much more comprehensive discussions of the theory of operation of GaAs lasers are available in the literature.[3,7]

In all types of lasers two criteria must be met for lasing to take place. These are (1) population inversion and (2) optical feedback. Population inversion is attained in GaAs lasers by passing a current in the forward direction through the diode.

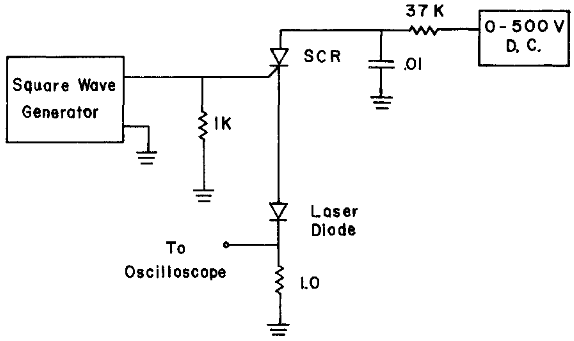

FIG. 1. Laser pulsing circuit. The SCR is an RCS 2N622. The resistance values are in ohms and the capacitance value is in microfarads. The 1.0-Ω resistor is used to monitor the current pulse.

For the diodes we used in these experiments, a current pulse of approximately 10 A, corresponding to a current density of approximately 10^4 A/cm^2, is necessary to attain laser action.

As these electrons cross the *p-n* junction they lose an amount of energy ΔE which is approximately equal to the energy difference between the conduction and the valence band at the junction of the forward biased diode. The wavelength of light emitted in this transition is then just

$$\lambda = hc/\Delta E.$$

Because the electron energies are distributed about the Fermi level at room temperature, the emitted light from the diode is also distributed in wavelength and not emitted at only a single wavelength. Recall that in equilibrium the probability of an electron being in an energy state E is

$$\rho(E) = \{\exp[(E - E_F)/kT] + 1\}^{-1}.$$

Great care must be exercised in using the equilibrium distribution since in actual operation approximately 10^{17} electrons/cm^2 pass through the laser during a pulse of approximately 10^{-6} sec duration. We can, however, make a sweeping approximation and assume that the same functional form for the probability holds[7] and that we can take into account the effects of all the other electrons by replacing E_F with E_F' which will be called the quasi-Fermi level. Having done this we realize that we now have a model which will predict what will happen as the temperature of the laser diode is changed. First we note that for the conduction band we can write

$$\rho(E_c) = \{\exp[(E_c - E_{Fc}')/kT] + 1\}^{-1} \quad (1)$$

and for the valence band

$$\rho(E_v) = \{\exp[(E_v - E_{Fv}')/kT] + 1\}^{-1}. \quad (2)$$

The condition for population inversion is simply that the probability of an electron having an energy E_c in the conduction band is greater than it having an energy E_v in the valence band,[3] i.e.,

$$\rho(E_c) > \rho(E_v),$$

or

$$[(E_c - E_{Fc}')/kT + 1]^{-1} > [(E_v - E_{Fv}')/kT + 1]^{-1},$$

which gives

$$E_c - E_v < E_{Fc}' - E_{Fv}'. \quad (3)$$

The first thing that we recognize from this expression is that

$$\lambda = hc/(E_c - E_v), \quad (4)$$

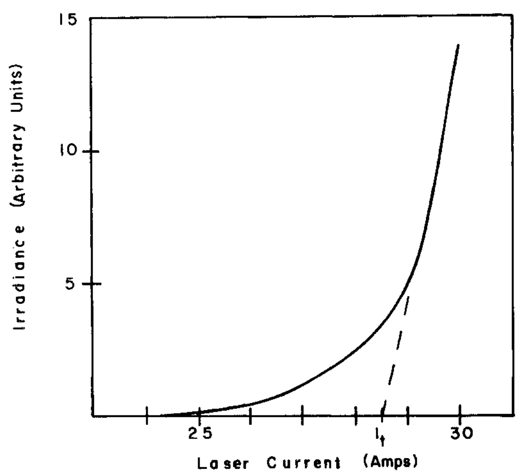

FIG. 2. The light emitted by the diode as a function of the current passing through it. The threshold current is defined as the linear extrapolation of the rapidly rising portion of the curve to the zero irradiance intercept.

where λ is the wavelength of the emitted light. What do these expressions tell about the change in the wavelength of the emitted light with temperature? First consider Eqs. (1) and (2). As the temperature is decreased the distribution of electrons contract about their respective Fermi levels. When this happens, we see from Eq. (4) that the energy of the emitted light increases and consequently the wavelength of the emitted light decreases.

The second criterion for lasing is that there must be a means of optical feedback. In most lasers this is provided by placing a pair of mirrors so that the emitted light is reflected back into the lasing medium. In GaAs lasers the surfaces of the diode are themselves polished and serve as mirrors. It is well known[11] that for a standing wave to be set up between two mirrors the following condition must be fulfilled:

$$m\lambda = 2\alpha L. \quad (5)$$

In this expression m is an integer, λ is the wavelength of the emitted light, α is the index of refraction of the GaAs junction, and L is the distance between the mirrors. It therefore follows that although the junction is capable of emitting a broad spectrum,· lasing action takes place only at the discrete wavelengths for which Eq. (5) is satisfied. Therefore, the laser emits not a single wavelength but a number of discrete modes which can be both spatially separated and separated in wavelength.

EXPERIMENTS

A. Introduction

The experiments described in this section were performed using GaAs lasers made by two manufacturers, a Monsanto MLI and Laser Diode LD 22-2. Both of these must be operated in the pulsed mode and emit light in the wavelength range 8500–9100 Å at room temperature. Many laser pulsing circuits are available in the literature.[12] The specific circuit that we used in these experiments is shown in Fig. 1. Depending on the experiment performed, the laser light was detected with either a photodiode (Texas Instruments H11) or a photomultiplier (RCA 7102).

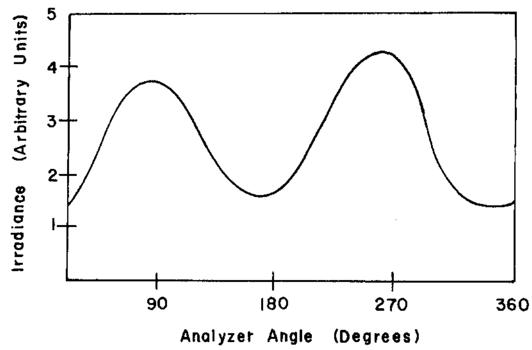

FIG. 3. Polarization of the emitted light. The irradiance of a single mode is recorded as a function of analyzer angle.

B. Lasing Threshold

The determination of lasing threshold for semiconductor lasers is a straightforward experiment. One needs only to record the relative irradiance of the emitted light as a function of the current passing through the laser diode. A typical observation is shown in Fig. 2. The lasing threshold current is determined by a linear extrapolation of the rapidly rising portion of this curve to the zero irradiance intercept. Using precisely the same apparatus the relative efficiency, i.e., the ratio of the output power to the input power, can also be measured as a function of the current passing through the diode. An interesting and informative set of experiments would be to record the irradiance of the emitted light and the relative efficiency as functions of current for both light emitting diodes and laser diodes. Comparison of the two sets of data shows the effects of optical feedback on the diode's operation characteristics.

C. Thermal Tuning

The discussion in the theory section suggests that information concerning the energy distribution of the electrons can be gained by studying the wavelength of the light emitted by the diode as a function of the diode's temperature. We obtained satisfactory results over a temperature of about 30°C by simply soldering a copper rod to the bottom of the outside of a copper can. The case of the laser is then carefully soldered to the end of the rod. The temperature of the laser is controlled by filling the can with liquid and holding the liquid at an appropriate temperature.

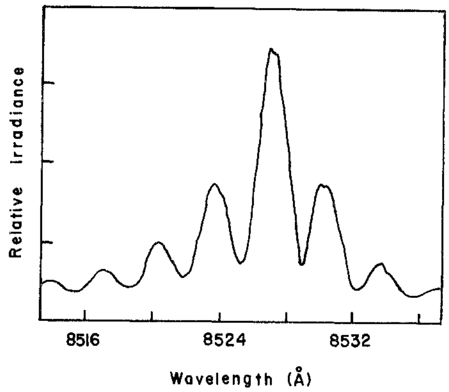

FIG. 4. Spectrum of the light emitted from a GaAs laser. The existence of various modes is clearly visible even with a moderate resolution spectrometer.

If thermal insulation is desired, it can simply be wrapped around the can. Because of condensation of water from the air, it was necessary to use a more sophisticated vacuum Dewar for temperatures much below 0°C. This device has been used in a recent cesium vapor optical pumping experiment.[13,14]

Measurements were performed by passing the laser light through a spectrometer and recording the irradiance as a function of wavelength at various temperatures. If the spectrometer has sufficient resolution (2–3 Å) the irradiance of each mode can be studied. If the modes cannot be resolved the shift of the unresolved peak can be recorded, and information similar to that presented by Kwansnoski[1] can be obtained.

D. Polarization

We have studied the polarization of the individual modes in two different ways. These two methods reflect ways that the individual modes of the emitted spectrum can be resolved. The first way to resolve the modes, which is simpler in terms of equipment requirements, exploits their spatial separation. If a small detector, e.g., a photodiode, is placed 3–5 cm from the laser, the irradiance can be recorded as a function of position along the junction plane. From this information the spacial position of the individual modes can be identified. After the photodiode has been positioned so that it detects the maximum irradiance from a given mode, a polarizing filter is placed between the laser and the photodiode. If the light is polarized, this filter acts as an analyzer. To determine the degree of polarization, rotate the analyzer through 360° recording irradiance as a function of angle at convenient angles. The degree of polarization is then defined as

$$P=(I_{\max}-I_{\min})/(I_{\max}+I_{\min}).$$

The degree of polarization can be studied as a function of current for the various modes.[10] A typical result is shown in Fig. 3. Acceptable results have been obtained using an analyzer as simple as a lens from a pair of polarizing sun glasses.

A more sophisticated and somewhat more informative experiment to determine the same information can be performed in the following way. The laser light is passed through a spectrometer before it is detected. The spectrometer must be capable of resolving peaks separated by approximately 2 Å. In this way a spectrum like that shown in Fig. 4 can be obtained. The spectrometer can be set to transmit only one mode, and polarization of the mode can be studied by simply inserting an analyzer in the light path between the laser and the spectrometer.

It should be emphasized that if one has the necessary apparatus to perform the above experiment one can also observe the growth of the modes as one passes through lasing threshold, the appearance of a second family of modes well above threshold, and shift of the relative irradiance of the individual modes as a function of diode temperature.

CONCLUSIONS

We have presented a few experiments exploiting the properties of GaAs lasers. It is intended that one or more of these could be adopted as a structured advanced undergraduate laboratory experiment or that a study of the properties of GaAs lasers could serve as an independent research project.

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† Present address: National Bureau of Standards, Washington, D. C. 20234.

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Conventions for Magnetic Quantities in SI

J. E. COLEMAN
Lanchester Polytechnic
Coventry, England

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Magnetic equations written in International Standard (SI) units usually use either the Sommerfeld convention ($\mathbf{m}=I\mathbf{A}$, $\mathbf{H}=\mathbf{B}/\mu_0-\mathbf{M}$) *or the Kennelly convention* [$\mathbf{m}'=\mu_0 I\mathbf{A}$, $\mathbf{H}=1/\mu_0(\mathbf{B}-\mathbf{M}')$]. *An alternative is the "SI electric" convention* ($\mathbf{m}=I\mathbf{A}$, $\mathbf{H}=\mathbf{B}-\mu_0\mathbf{M}$) *proposed by Stopes-Roe. In this paper it is shown that the "SI electric" convention arises naturally from the comparison of pole and current loop models for magnetic materials, and hence overcomes the problems of illogical factors of* μ_0 *inherent in the Sommerfeld and Kennelly formulations. This approach clarifies the roles of the field vectors* **B** *and* **H**.

"...we make no recommendation regarding magnetic units." With this statement the Coulomb's Law Committee[1] (CLC) concluded its discussion of the relative merits of the "Sommerfeld" and "Kennelly" conventions for International Standard (SI) magnetic equations. They pointed out that for people working with magnetic poles, Kennelly is superior to Sommerfeld; but, the opposite is true for those using Amperian current loops. An illogical μ_0 appears if Sommerfeld is used with poles or if Kennelly is used with current loops. As a result of these drawbacks neither convention has won complete acceptance. Thus more than 20 years after the publication of the CLC report, both remain in common use. The confusion arising from the use of two conventions has hampered the change to SI and the majority of magnetism research workers continue to prefer cgs units.

How much longer will this unsatisfactory situation persist? There seems to be a marked preference for Sommerfeld in modern undergraduate physics texts, reflecting the strong move away from poles to current loops in elementary work. If such texts introduce **H** at all, it is as a convenient symbol for $(\mathbf{B}/\mu_0)-\mathbf{M}$, just as **D** is a convenient symbol for $\epsilon_0\mathbf{E}+\mathbf{P}$ in electrostatics. However, this underates the importance of **H** in the pole approach as we shall see below. This preference for Sommerfeld in physics textbooks is