Computer-assisted experiments with a laser diode

2011 Eur. J. Phys. 32 793

(http://iopscience.iop.org/0143-0807/32/3/015)

IOP Publishing European Journal of Physics

Eur. J. Phys. **32** (2011) 793–802 doi:10.1088/0143-0807/32/3/015

Computer-assisted experiments with a laser diode

Yaakov Kraftmakher

Department of Physics, Bar-Ilan University, Ramat-Gan 52900, Israel

E-mail: krafty@mail.biu.ac.il

Received 29 December 2010, in final form 7 March 2011
Published 4 April 2011
Online at stacks.iop.org/EJP/32/793

Abstract
A laser diode from an inexpensive laser pen (laser pointer) is used in simple experiments. The radiant output power and efficiency of the laser are measured, and polarization of the light beam is shown. The h/e ratio is available from the threshold of spontaneous emission. The lasing threshold is found using several methods. With a data-acquisition system, the measurements are possible in a short time. The frequency response of the laser diode is determined in the range 10–10^7 Hz. The experiments are suitable for undergraduate laboratories and for classroom demonstrations on semiconductors.

(Some figures in this article are in colour only in the electronic version)

1. Laser diode for beginners

1.1. The laser

The laser (light amplification by stimulated emission of radiation) is one of the outstanding achievements in physics of the 20th century [1–4]. The first laser appeared in 1960, though all the principles of such a device were known long before; moreover, these principles were already realized in similar microwave devices (masers). The basic principles of lasers are the following.

- *Population inversion* is needed for continuously emitting photons: the number of particles n_2 in an excited state of energy E_2 should exceed the number of particles n_1 in a lower energy state of energy E_1. At thermal equilibrium,

$$n_2/n_1 = \exp(-\Delta E/k_B T), \tag{1}$$

  where $\Delta E = E_2 - E_1$, k_B is Boltzmann's constant and T is the absolute temperature. Thus, the population inversion, where $n_2 > n_1$, is a nonequilibrium state. The process of supplying the energy required for inverting the population is called pumping; the necessary energy is supplied as an electric current or as light at a different wavelength.

- *Stimulated emission*. Electromagnetic emission can be spontaneous or stimulated. The presence of photons of energy ΔE can stimulate the transition from the upper energy level to the lower level. Photons generated by stimulated emission are strictly similar to primary photons in direction, wavelength, phase and polarization. The concept of stimulated emission was introduced by Einstein in 1916, long before the masers and lasers were developed. Together with the optical feedback (see below), this gives the laser output light its characteristic coherence and directionality and allows it to maintain uniform polarization and monochromaticity. To maintain constant populations n_2 and n_1, the rate of pumping must balance the spontaneous and stimulated emission. The stimulated emission triggered by light passing through the laser medium can overcome the losses, so the light will be amplified.
- *Optical feedback* with an optical cavity, together with the stimulated emission, forms a highly directed light beam. Two mirrors confining the laser medium produce in it standing wave patterns called modes. Light bounces back and forth between the mirrors, each time passing through the medium. One of the two mirrors is partially transparent, and the output beam is emitted through it. The laser medium amplifies any passing photons, but only photons in a mode supported by the optical cavity will pass more than once through the medium and receive substantial amplification. If the gain in the laser medium is larger than the losses, then the power of the light inside the cavity can rise exponentially. However, each stimulated emission event returns an atom from its excited state to the ground state, thus reducing the gain of the medium. The minimum pump power needed to begin the laser action is called the lasing threshold; the term originates from 'laser'.

1.2. The laser diode

The most common type of laser diode is formed from a p–n junction [5–11]. The crystal is doped to produce an n-type region and a p-type region, one above the other. Forward electrical bias across the diode causes the holes and electrons to be injected from opposite sides of the junction into the active region. The recombination of electrons and holes results in emission of photons. The emission wavelength is basically determined by the band-gap energy of the active-region material. The band-gap energy of ternary and quaternary semiconductor compounds can be adjusted in a certain range by varying their composition. The devices are sometimes referred to as injection laser diodes to distinguish them from optically pumped laser diodes.

A photon of energy equal to the recombination energy can cause stimulated emission. This process generates another photon of the same frequency, travelling in the same direction, with the same polarization and phase as the first photon. The optical gain in the injection region increases with the number of electrons and holes injected into the active region. The optical bandwidth of output light amounts to a few nanometres.

Laser diodes differ from other lasers in several important respects [8]: (i) the transitions are associated with the band properties of semiconductors; (ii) because the active region is very narrow, the divergence of the laser beam is larger; (iii) the spatial and spectral characteristics are strongly influenced by the variations of the band-gap energy and refractive index; (iv) the laser action is triggered simply by passing a forward current, so a high efficiency and modulation at high frequencies are achievable.

The first laser diodes were homojunction diodes, where the material of the core layer and that of the surrounding clad layers were identical. Then heterostructures employing layers of varying band gap and refractive index were recognized as advantageous. Contemporary laser diodes, first demonstrated in 1970, are more complicated double-heterostructure diodes. In

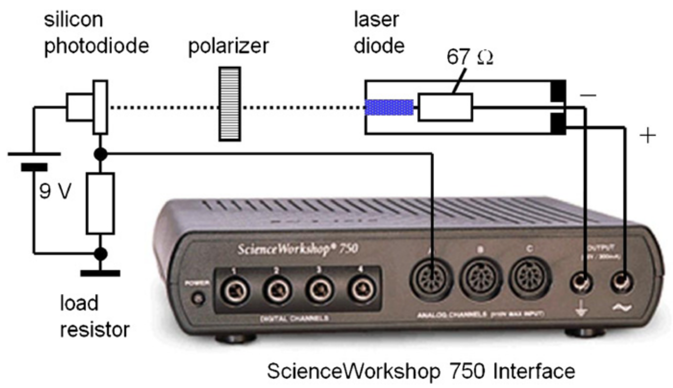

Figure 1. The setup with the modified laser pen, polarizer and silicon photodiode.

2000, Zhores Alferov and Herbert Kroemer shared the Nobel Prize in Physics 'for developing semiconductor heterostructures used in high-speed and optoelectronics'. The efficiency of modern laser diodes (that is, the ratio of the radiant output power to the input electric power) amounts to 50% and even more.

2. The setup

A laser diode from a laser pen (laser pointer) is used in the experiments. Its emission wavelength appeared to be 660 nm. The batteries operating the laser pen were removed, and two wires were used to connect the device to an external dc supply. One of the wires (minus) is fixed inside the pen with a plastic tube. The second connection (plus) is on the metal case of the pen (figure 1). The laser switch is fixed in the 'on' position. Usually, a laser diode includes an electronic driver preventing the device from damage. In the driver, a photodiode sensing the output light governs a transistor put in series with the laser diode. Such a driver is not included in an inexpensive laser pen. Instead, a limiting resistor is positioned inside the case and connected in series with the laser diode; in the laser pen used, the limiting resistance is 67 Ω.

With a data-acquisition system, the measurements are possible in a short time. We use the PASCO *ScienceWorkshop* data-acquisition system with the *DataStudio* software. The input electric current and power, radiant output power and efficiency of the laser can be measured or calculated and displayed as functions of the voltage applied to the device or of the current through it. The *signal generator* incorporated into the *ScienceWorkshop 750 Interface* feeds the laser diode. The *output voltage* is the *positive ramp-up* voltage linearly increasing from zero to a maximum value set to be safe for the laser. The period of the *output voltage* is 20 s, and the *sample rate* is 100 Hz. The input current is taken as the *output current* of the *signal generator*, and the voltage applied to the laser diode as the *output voltage* minus the *output current* times the limiting resistance. The *signal generator* operates in the *auto* mode: it generates the *output voltage* after starting a run. The option *automatic stop* is used for automatically ending each run.

3. Measurements and results

3.1. Radiant output power and efficiency

This experiment is similar to that described by Ojeda *et al* [12]. For determining the radiant output power, the laser beam is directed onto a silicon photodiode (United Detector Technology, PIN-10D) operated with a 9 V battery. The *voltage sensor* acquires the voltage on a 1 kΩ load of the photodiode. The radiant power P of the laser diode is calculated from the photoelectric current and the spectral response of the photodiode, $R(\lambda)$, the ratio of the photodiode current I to the incident light power P. In the range 400–800 nm, the spectral response of the photodiode used can be approximated as

$$R(\lambda) = I/P \ (\mathrm{A\ W^{-1}}) = 1.2 \times 10^{-3}(\lambda - 300), \qquad (2)$$

where λ is the wavelength in nanometres. With minor variations, this relation holds for all silicon photodiodes. For $\lambda = 660$ nm, the I/P ratio is taken as 0.43 A W^{-1}. With this value, *DataStudio* calculates the radiant output power and efficiency of the laser diode. This approach is not as precise as the use of a sensor based on the thermal action of absorbed light, but is much simpler and quite sufficient for our aims.

During a run, the *output voltage* of the *signal generator* increases linearly from 0 to 3.5 V, while the voltage applied to the laser diode to nearly 2.3 V. The data are displayed versus the applied voltage (figure 2). Two threshold points are seen on the plots: rise of the input current and power near 1.8 V, and rise of the radiant output power and efficiency near 2.1 V. The first point shows the threshold of spontaneous emission, and the second the lasing threshold. For the maximum applied voltage, the radiant output power amounts to 2 mW. The laser efficiency increases with the applied voltage and reaches nearly 0.05, but further increase of the voltage may destroy the laser. The measurement data are well reproducible. This experiment can be used as a laboratory work and/or as a classroom demonstration of two thresholds in the laser action and of the efficiency of a laser diode.

It is possible to increase the laser efficiency by applying pulsing voltage. Such experiments could only be recommended when a laser diode is reliably protected from exceeding the limit of average dissipated power.

3.2. Spontaneous emission and the h/e ratio

Spontaneous emission from a laser diode appears when the applied voltage reaches a definite value V_F, the forward 'turn-on' voltage. The energy of photons emitted is close to eV_F. Therefore, $h/e \cong \lambda V_F/c$, where h is Planck's constant, e is the electron charge, c is the speed of light and λ is the emission wavelength. Since the values of V_F and λ are easy to measure, this possibility of determining the h/e ratio is very attractive. Many such measurements were done with light-emitting diodes (LEDs). With LEDs of different colour, the results obtained are reasonably close to the correct h/e value [13–15]. This approach causes objections [16, 17] because of the assumptions accepted. It was also shown that the energies of photons emitted by four LEDs are by 7–20% smaller than the band-gap energies; on the other hand, the photon energies appeared to be significantly higher than those corresponding to the 'turn-on' voltages [18]. The precise values of the h/e ratio could not be expected from such measurements, but it is worth looking for an LED (or a laser diode) providing a more or less correct result.

In our measurements, the 'turn-on' voltage is determined from the rapid rise of the input current and of the radiant output power; the spontaneous emission starts at 1.85 ± 0.05 V (figure 3). From these data, the h/e ratio is $(4.07 \pm 0.1) \times 10^{-15}$ J s C^{-1}, very close to the

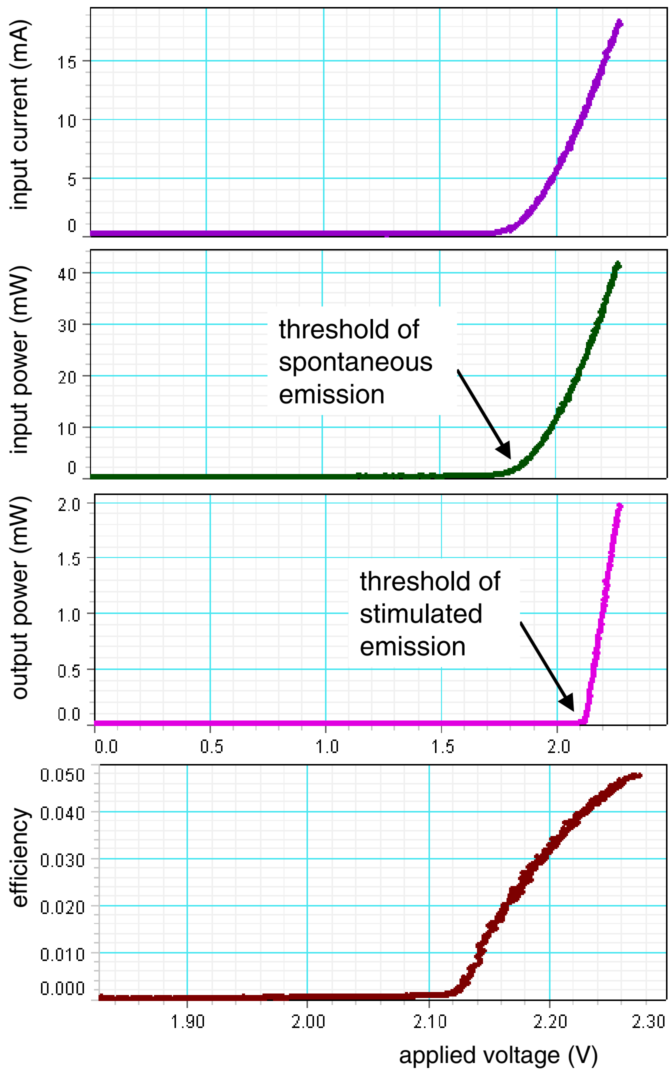

Figure 2. Characteristics of the laser diode versus applied voltage.

correct value. The students can calculate the h/e ratio in the course of demonstrating the 'turn-on' voltage.

3.3. Lasing threshold

Within the cavity, the optical gain g due to stimulated emission is compensated by the optical loss α due to absorption. The net gain as a function of the distance z is given by [8]

$$\exp\left[(g-\alpha)z\right]. \tag{3}$$

Taking into account the reflections R_1 and R_2 of the two mirrors confining the cavity, the total optical gain will be positive when

$$R_1 R_2 \ \exp\left[(g-\alpha)2L\right] > \ 1, \tag{4}$$

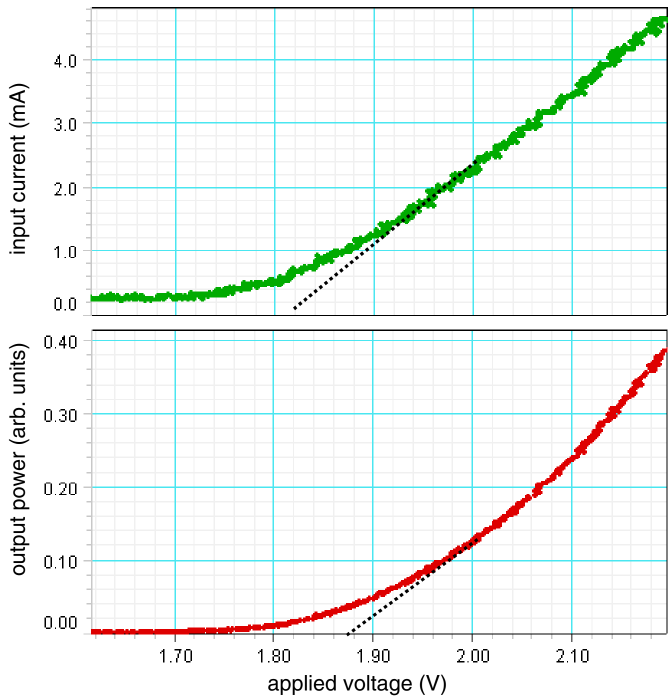

Figure 3. Input current and radiant output power close to the threshold of spontaneous emission. From the extrapolations, the threshold point can be taken as 1.85 ± 0.05 V.

where L is the length of the laser cavity. The threshold gain for lasing, g_{th}, thus equals

$$g_{th} = \alpha + (1/2L)\ln(1/R_1R_2). \tag{5}$$

Therefore, the lasing threshold depends on the laser design. The injected electron concentration is proportional to the input current, so the optical gain also has a linear dependence on the current. Two methods are used here for determining the lasing threshold. First, the radiant output power and efficiency rapidly increase above the threshold. Second, the emission line for the stimulated emission becomes much narrower than that for the spontaneous emission.

The spectrum of the output light is determined using a monochromator with a reflecting grating having 1200 grooves per millimetre. The monochromator output is scanned by the PASCO *light sensor* (CI-6504A) with the *aperture bracket* (OS-8534A); the *rotary motion sensor* (CI-6538) and *linear translator* (OS-8535) are also employed in the measurements. The width of the emission line is determined as the full width at half maximum. The resolution of our measuring system is insufficient to observe details of the spectrum, but the narrowing of the emission line above the lasing threshold is clearly seen. The lasing threshold is 2.12 ± 0.02 V (figure 4). Measurement data below and above the threshold (2.064 and 2.134 V) are shown in the two insets; note the difference in the vertical scales.

The plots of the radiant output power and of the efficiency of the laser diode demonstrate the lasing threshold.

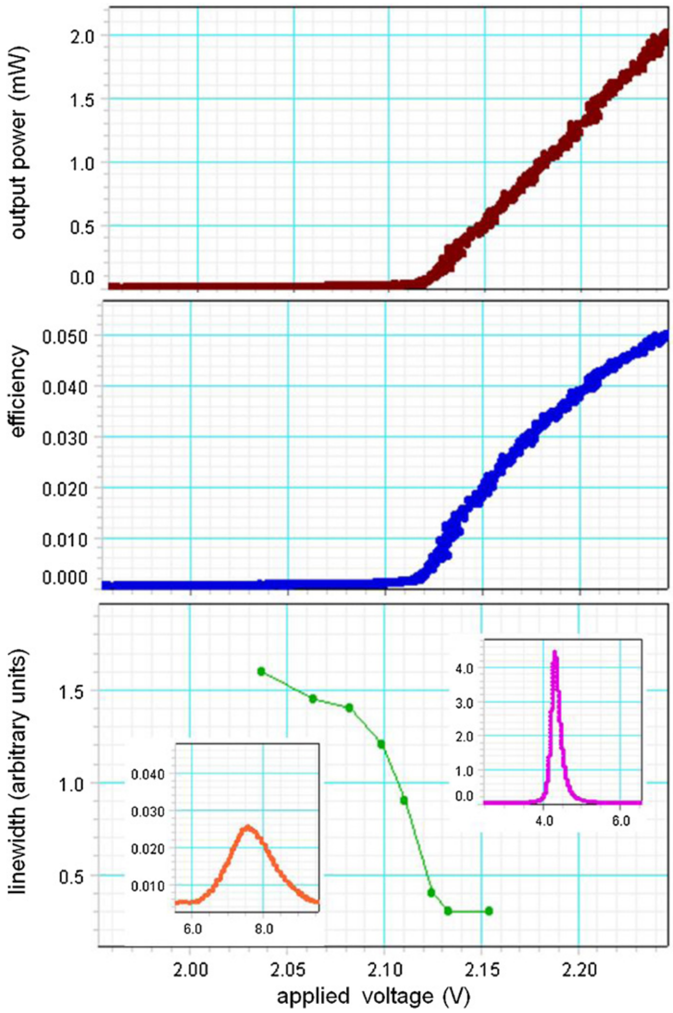

Figure 4. Characteristics of the laser diode close to the lasing threshold: the radiant output power, efficiency and emission line width. In the insets, the horizontal scale is nearly the same, while the vertical scales differ by a factor of 100.

3.4. Polarization of output light

The stimulated emission generates photons polarized exactly like the primary photons. The polarization is measured with a usual polarizer (PASCO OS-8473) placed in front of the laser diode. One run is performed when the polarizer is set for a maximum signal from the photodiode, I_{max}, and the second for a minimum, I_{min}. The measure of the polarization is the ratio $(I_{max} - I_{min})/(I_{max} + I_{min})$. From the data obtained (figure 5), the maximum-to-minimum ratio equals nearly 100. With this ratio, the polarization of the laser beam is 98%, which is a common value for such laser diodes.

3.5. Modulation characteristics

Laser diodes are easily modulated sources and find wide use in optical communications [19]. Optical fibres are commonly used with infrared light due to less attenuation and dispersion.

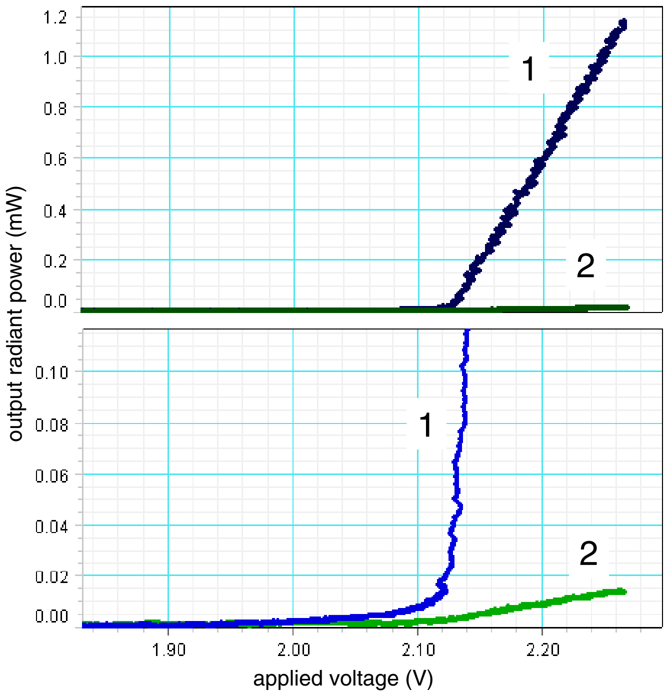

Figure 5. Optical output power versus applied voltage after passing a polarizer set for the maximum (1) and minimum (2) signals. The vertical scale of the bottom graph is ten times enlarged. Above the lasing threshold, the maximum-to-minimum ratio is nearly 100.

The signal encoding is typically simple intensity modulation. Free space optics systems can function over distances of several kilometres when there is a clear line of sight between the transmitter and the receiver. A broad frequency band is necessary for simultaneously transmitting many programs. A linear amplitude characteristic is also important.

When a current step above the threshold value is applied to a laser diode, a delay of a few nanoseconds occurs before the stimulated emission is observed. When the input current, above the lasing threshold, is modulated with a small ac signal, the radiant output power follows the modulation waveform but only to a certain frequency limit. For laser diodes intended for optical communications, this limit lies in the gigahertz range. In fact, the frequency band may be strongly limited by parasitic resistance and capacitance of the device.

The frequency limit of a laser diode depends on the average photon lifetime in the cavity before the photons are lost from absorption or emission through the two mirrors. High doping levels are needed for achieving broad frequency bands.

LEDs and laser diodes were already employed in student experiments on optical communications [20–22].

The modulation characteristics of the laser diode are determined with a function generator (Hewlett-Packard 33120A). The setup for the measurements is similar to that used earlier [22]. A dc supply and the function generator, each with a 100 Ω resistor added at the output, are connected to the laser in parallel. The output voltage of the dc supply is adjusted to obtain a sufficient radiant output of the laser. The ac output voltage of the function generator is set several times smaller than this dc voltage. The laser beam is directed onto a fast

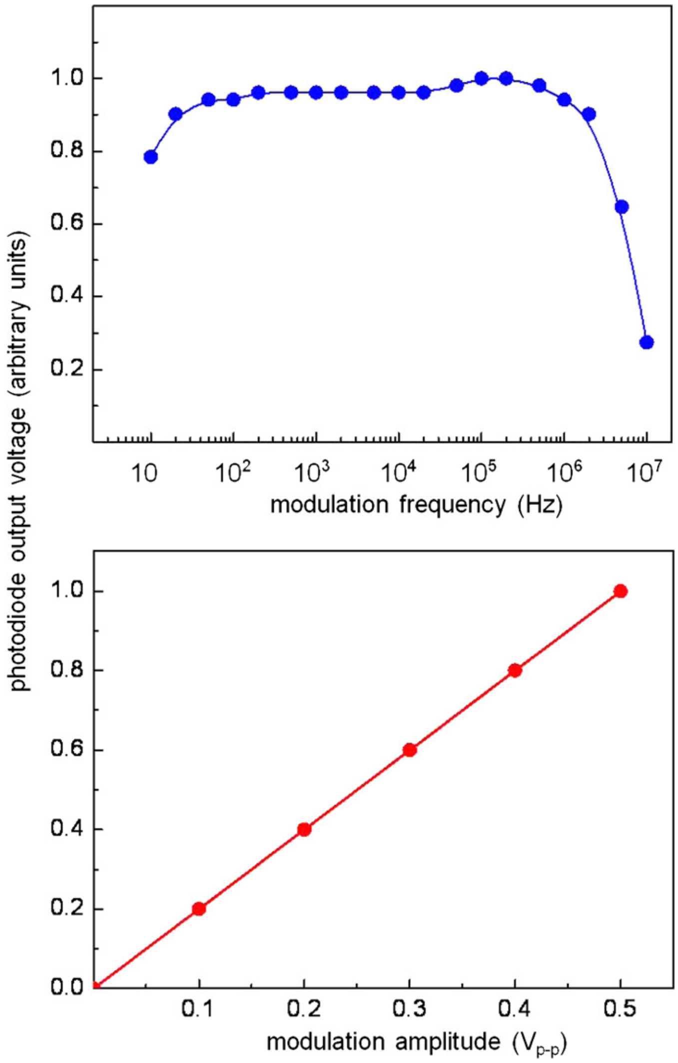

Figure 6. Modulation characteristics of the laser diode.

photodiode (United Detector Technology, PIN-5D) operated with a 9 V battery. The signal on a 100 Ω load of this photodiode is observed with an oscilloscope (Kenwood CS-4025). The same oscilloscope serves for monitoring the voltage applied to the laser diode. The frequency response is determined in the 10–10^7 Hz range (figure 6). The amplitude characteristic measured at 100 kHz by changing the modulating voltage is fairly linear.

Since the laser diode has inherent capacity, the real voltage across the *p*–*n* junction becomes frequency dependent at high frequencies. The frequency response presented here relates to the ac voltage at the output of the function generator.

The setup used for determining the frequency response of the laser diode is suitable for demonstrating voice transmission. The function generator should be replaced by an audio amplifier with a microphone; another audio amplifier with a loudspeaker acquires the signal from the photodiode. With a video camera and a monitor, video signals can be transmitted with the laser beam; the use for this aim of an LED and a light guide was described earlier [22].

4. Conclusion

The experiments considered include many topics (semiconductors, quantum mechanics, lasers, optical communications, electrical and optical measurements), but they are quite accessible to undergraduate students. The experiments or parts of them may be employed in undergraduate laboratories and used as classroom demonstrations.

Acknowledgment

Many thanks to the referee for useful recommendations.

References

[1] Hecht E 1994 *Physics* (Pacific Grove, CA: Brooks /Cole) pp 818–20 1062–65
[2] Jenkins F A and White H E 1981 *Fundamentals of Optics* 4th edn (Auckland: McGraw-Hill) pp 632–57
[3] Jackson M, Bauen D and Hasbun J E 2001 Investigation of laser fundamentals using a helium–neon laser *Eur. J. Phys.* **22** 211–8
[4] Henningsen J 2011 Teaching laser physics by experiments *Am. J. Phys.* **79** 85–93
[5] Jones K A 1987 *Introduction to Optical Electronics* (New York: Wiley) pp 282–315
[6] Ogasawara N 1994 Lasers, semiconductor *Encyclopedia of Applied Physics* vol 8 (New York: VCH) pp 425–42
[7] Streetman B G and Banerjee S 2000 *Solid State Electronic Devices* 5th edn (Upper Saddle River, NJ: Prentice-Hall) pp 396–410
[8] Sze S M and Ng Kwok K 2007 *Physics of Semiconductor Devices* 3rd edn (Hoboken, NJ: Wiley) pp 621–51
[9] Wikipedia, key words: laser, laser diode, laser pointer, lasing threshold, optical cavity, optical communication
[10] http://www.rp-photonics.com/laser_diodes.html
[11] http://www.repairfaq.org/sam/laserdio.htm
[12] Ojeda A M, Redondo E, González Diaz G and Mártil I 1997 Analysis of light-emission processes in light-emitting diodes and semiconductor lasers *Eur. J. Phys.* **18** 63–7
[13] O'Connor P J and O'Connor L R 1974 Measuring Planck's constant using a light emitting diode *Phys. Teach.* **12** 423–5
[14] Nieves L, Spavieri G, Fernandez B and Guevara R A 1997 Measuring the Planck constant with LEDs *Phys. Teach.* **35** 108–9
[15] Zhou F and Cloninger T 2008 Computer-based experiment for determining Planck's constant using LEDs *Phys. Teach.* **46** 413–5
[16] Holcomb D F 1997 LEDs: their charm and pitfalls *Phys. Teach.* **35** 198
[17] Morehouse R 1998 Answer to Question #53 Measuring Planck's constant by means of an LED *Am. J. Phys.* **66** 12
[18] Precker J W 2007 Simple experimental verification of the relation between the band-gap energy and the energy of photons emitted by LEDs *Eur. J. Phys.* **28** 493–500
[19] Kogelnik H 1995 Optical communications *Encyclopedia of Applied Physics* vol 12 (New York: VCH) pp 119–55
[20] Kraftmakher Y 2003 Telemetry in the classroom *Phys. Teach.* **41** 544–5
[21] Lee S K, Kim D I, Kim G-N and Cho D 2006 Voice transmission via frequency-modulated diode laser light *Am. J. Phys.* **74** 1037–9
[22] Kraftmakher Y 2008 Video through a light guide *Am. J. Phys.* **76** 788–91