RESEARCH ARTICLE

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Microcontroller-Based Thermoelectrically Stabilized Laser Diode System

Muddasir Naeem[1],* , **Saqlain Tariq Sahi[1]**, **Tayyab Imran[1]** and **Muhammad Abuzer[2]**

[1]*Department of Physics, Lahore University of Management Sciences, Pakistan*

[2]*Electrical Engineering Department, Lahore University of Management Sciences, Pakistan*

Abstract: This work aims to describe the development of a prototype laser diode system along with its driver circuit and a stable microcontroller-based thermoelectric cooling system. The laser diode driver circuit was designed and simulated by using NI Multisim. The driver circuit was built using two LM317 ICs to control the voltage across the laser diode and current through the laser diode. The laser diode output power varies by varying the current across the laser diode through the driver circuit. The temperature of the laser diode rises with time, affecting the output power of the laser diode during a long period of operation. A microcontroller-based cooling system was designed and fabricated using thermoelectric coolers. The microcontroller controls the cooling system ON/OFF period to maintain the laser diode at a particular temperature by removing the excess heat produced during the lasing action. The laser diode with a microcontroller-based cooling system shows that the laser diode output power remains stable during a long period of operation.

Keywords: driver circuit, microcontroller, thermoelectric cooler, temperature sensor, multisim

1. Introduction

A laser diode is a semiconductor device that converts electrical energy into light energy. They are compact, efficient, and use low current (Silfvast, 2004). They are the most significant for control and communication-based applications because of the simplicity of their use, efficiency, and natural compatibility with the rest of the modem electronics (Verdeyen, 1989). Semiconductor lasers primarily comprise P-N junctions, which are excellent photon sources, converting injected electrons into light beams. Water purification, bar-code scanning, range finders, LIDAR systems, laser designators, illuminators, small bio-agent detection systems, analytical devices for biotechnology and medicine, currency screening, UV curing, and quick prototyping are all applications for semiconductor optoelectronic devices (Harder & Sprague, 2010; Kneissl et al., 2007). Semiconductor lasers can serve applications where size, weight, and power are critical operational factors (Liang et al., 2015). Visible laser diodes provide a fast direct modulation rate and high pumping efficiency with no droop effect, making them a research focus for creating alternative visible light communication (VLC) systems. Hanson et al. performed 532 nm VLC at 1 GB/s across a 2-m water pipe (Hanson & Radic, 2008). For digital video disc (DVD) applications, pulsing laser diodes that work at 650 nm are needed. They are moving to a lower wavelength than 780 nm, increasing storage capacity from 680 MB to 4.7 GB. Laser functioning in such DVD systems is optimum at temperatures over 70°C. This condition is challenging to meet with GaInP lasers because their performance suffers at high temperatures due to substantial, thermally triggered drift currents within the

p-doped cladding layers and the material system's high thermal resistance (Bour et al., 1993; Hatakoshi et al., 1988; Smowton & Blood, 1995). Temperature-dependent current characteristics explicate exponential increase in threshold current with an increase in temperature. The output power decreases nonlinearly with an increase in temperature (Yoshida et al., 2011). A coolant recirculation loop for high-power laser diodes was reported. This loop lets the diode bar heat exchangers work at their design coolant Reynolds number while using as little as 20% of their nominal coolant supply inflow (Vetrovec, 2008). A high-precision laser diode thermostat with TEC and system-optimized thermostat settings using proportional–integral–derivative control was designed for the high-precision wavelength testing, which computed TEC's cooling power based on LD's thermal load (Li et al., 2014). A micro heat exchanger was made and tested for cooling high-power laser diodes. The results of thermal tests showed that the cooling system kept the flow of liquid and the heat transfer rate the same across the whole surface of the micro heat exchanger while keeping the pressure drop low at high flow rates (Datta & Choi, 2015). Air cooling is enough for some lasers, but water cooling is needed in high-power lasers due to excess heat. In low-power laser diodes, a small amount of heat is produced, which does not affect the performance of the laser diode. However, when operated for an extended period, the temperature of the laser diode increases. Because of that, the cavity becomes unstable, which reduces the efficiency of the laser diode, and in some cases, the crystal gets damaged. To improve the performance of the laser diode for an extended period by maintaining the temperature, a low-cost thermoelectric cooler-based cooling system control along the microcontroller is designed and fabricated. The performance of the laser diode with the proposed cooling system design is much better

*Corresponding author: Muddasir Naeem, Department of Physics, Lahore University of Management Sciences, Pakistan. Email: muddasirnaeem98@gmail.com

and can be operated for extended periods without any fluctuation in output power. The proposed design is expected to reduce the damaging probability of the crystal because of temperature increase and the current overflow.

This article is constituted as follows: the design and simulation of the laser diode driver circuit are explained in Section 2. The description of the laser diode with the driver circuit is reported in Section 3. Microcontroller-based cooling system design and working are described in Section 4. Characterization of the laser diode with a microcontroller-based cooling system is documented in Section 5.

2. Laser Diode Driver Circuit

There is some range of voltage and current at which the laser diode works appropriately; the laser diode threshold and the maximum operating current are very low (usually milli-amperes) (Hager et al., 2012; Patil & Gautam, 2004). Depending upon the laser diode properties, the driver circuit is designed to control the current and applied voltage; otherwise, the laser diode gets damaged due to excess current. The specifications of the laser diode under study are given in Table 1.

Table 1
Specifications of the laser diode under study

Wavelength	650 nm
Maximum output power	8 mW
Maximum operating voltage	5.5 V
Maximum operating current	35 mA
Rise and fall time	0.5 ns
Operating temperature	−10°C to +40°C

A driver circuit controls the voltage and current passing the laser diode. Higher currents can induce damage. The laser diode driver circuit will give the control to supply the required current value to operate the laser diode. The laser diode circuit is designed and simulated to understand the voltage, current, and power behavior. The circuit shown in Figure 1 is implemented in designing and fabricating the laser diode driver circuit. NI Multisim (https://www.multisim.com/) electrical/electronic circuit simulation software tools were used for these simulations (Naeem et al.,

Figure 1
Circuit diagram of driver circuit
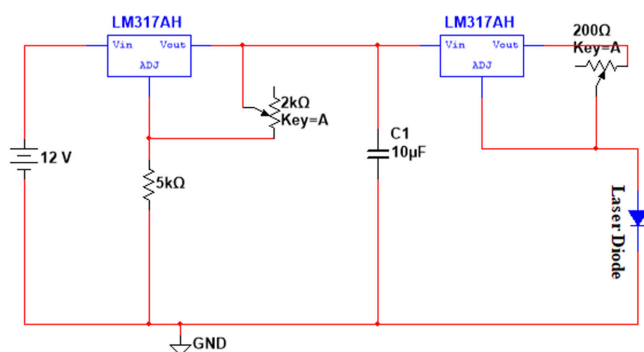
2021, 2022b). In Figure 1, a 12 V DC power supply and two LM317 ICs are used to control the voltage and current across the laser diode. One LM317 is used as a voltage regulator IC to provide a fixed output voltage; the output voltage of the IC can be controlled by changing the value of the variable resistor (2kΩ). The second LM317 IC is used as a current regulator IC to provide a fixed output current; a potentiometer (200Ω) is used instead of resistors at the output to control the output power of the laser diode (Udayasri et al., 2016; Zhimwang et al., 2019).

Figure 2 shows the simulated waveform of the voltage, temperature, power, and current across the laser diode at room temperature (25°C). The graph in Figure 2(a) shows no voltage (red) across the laser diode initially. The voltage across the laser diode increases, but there is no current (green) across the laser diode as the threshold voltage is not reached. When the voltage across the diode reaches the threshold (1.7 V), current flows through the laser diode. As the voltage increases, the current will also increase through the laser diode to a particular value (set according to the current controller). Once that value is reached, no matter how much voltage is applied at the input (source voltage), the voltage across the laser diode and the current flowing through it will not increase because of the current and voltage controller. So, we can limit the current and voltage across the laser diode to control the output power and reduce the damage probability of the laser diode (Avramescu et al., 2009).

In Figure 2(b), the graph shows that as the voltage (red) across the laser diode increases, the power (green) output of the laser diode also increases. No increase in power and voltage is observed after a certain specified voltage, regardless of the input voltage. Using a voltage controller circuit, the voltage across the laser diode is limited to a specific value, so there is no change in power because the circuit only allows a particular voltage limit across the laser diode. In Figure 2(a) and (b), time is not considered because only the change in power, current, and voltage across the laser diode with respect to the voltage supplied from the source is simulated. Figure 2(c) shows the transient (along time) behavior of voltage (red) and power (green) across the laser diode. In the simulated results, t = 0 corresponds to the point of no voltage across the laser diode. The driver circuit can control the voltage and current across the laser diode, but the temperature will increase with time. The simulation results show that as the temperature rises, the power of the laser diode will decrease, as shown in Figure 2(d), because of the thermal effect (Balasubramanian & Madhan, 2010). In Figure 2(d), the input voltage (voltage from the source) and the voltage across the laser diode are constant. We are only studying the effect of temperature increase on the laser diode output power for an extended period of operation at a fixed voltage and current. When the laser diode is operated for a long period, the laser diode temperature increases and because of that, the laser cavity becomes unstable and power loss occurs. The crystal gets damaged permanently if the temperature exceeds a specific limit.

3. Characterization of Laser Diode

The laser diode is characterized experimentally to check the compatibility of simulated results of the laser diode driver circuit. The results presented in Figure 3 are experimentally acquired for the laser diode configuration shown in Figure 1. The ambient temperature for the experimentally acquired results is 25°C. Figure 3(a) shows the behavior of the current and output power of the laser diode along the applied voltage. The current and output power increases linearly with the applied voltage across the laser diode. The current reaches the minimum value required for

Figure 2
(a) Current and voltage variation across laser diode along input voltage. (b) Power and voltage variation across laser diode along input voltage. (c) Power and voltage variation across laser diode along time. (d) Variation of output power along laser diode temperature
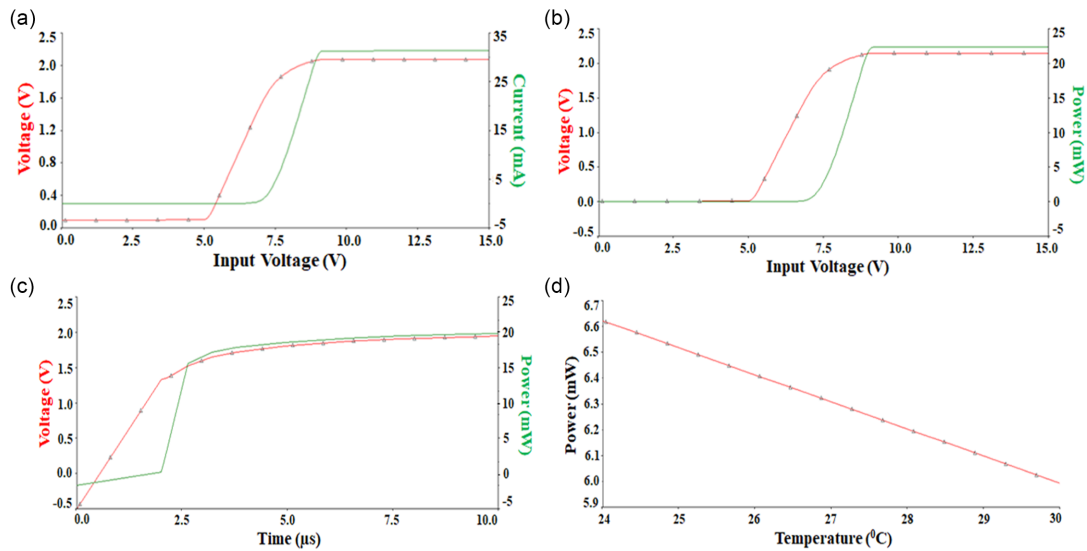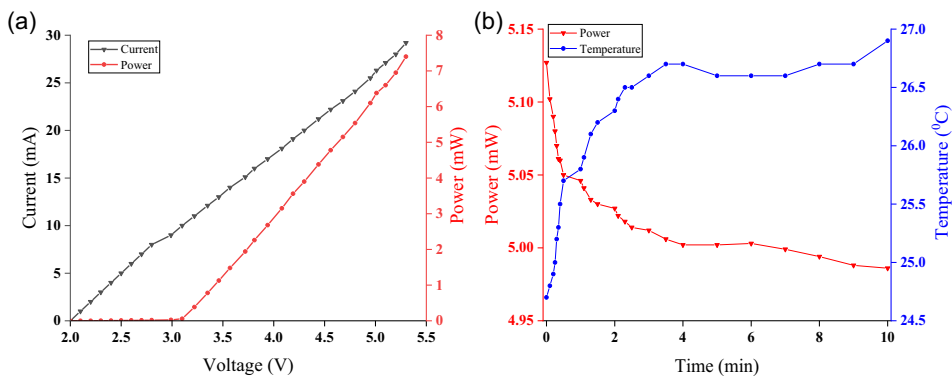

Figure 3
(a) Power and current variation along voltage. (b) Laser diode power output and temperature variation along time


recombining electrons and holes at the threshold applied voltage. As a result, radiation is emitted, and the laser output is obtained from the active area of the laser diode. Beyond the threshold voltage, the laser system's current and output power increases with applied voltage (Avramescu et al., 2009; Zhao et al., 2017). The graph shows that the threshold voltage of the laser system is 2.5 V, and output power increases with the applied voltage. The maximum output power of the laser system is around 7.4 mW at a current of approximately 30 mA, as shown in Figure 3(a). If more current is applied to increase the output power, the laser diode crystal gets damaged permanently by current overflow (Naeem et al., 2022a). The graph (Figure 3(b)) shows the variation in the output power and temperature of the laser diode over time when it is operated at some fixed applied current for an extended period with only air cooling. The temperature rises when the laser diode is operated for an extended period. As the temperature rises, the losses within the cavity increase, and with that, the output power of the laser diode continuously decreases with time (Ab-Rahman & Shuhaimi, 2012;

Yoshida et al., 2011). From Figure 3(b), it can be observed that the temperature significantly impacts the performance of the laser diode, so it is essential to control the temperature for high-performance, stable, and long-term operation (Deng et al., 2019; Zyoud et al., 2020). Thus, a microcontroller-based temperature control system is designed to reduce the effect of temperature, which is explained in Section 4.

4. Microcontroller-Based Thermoelectric Cooling System

A cooling system for a laser diode with a microcontroller is designed using a thermoelectric cooler. Some critical components of the cooling system are Arduino (Kuria et al., 2020), a thermoelectric cooler (Guo et al., 2020), and a temperature sensor (DS18B20) (Saha et al., 2021). Arduino microcontroller has an operating voltage of 5 V; input voltage of 7–12 V is recommended. However, if supplied with less than 7 V, the 5 V

Figure 4
Circuit diagram of microcontroller-based cooling system
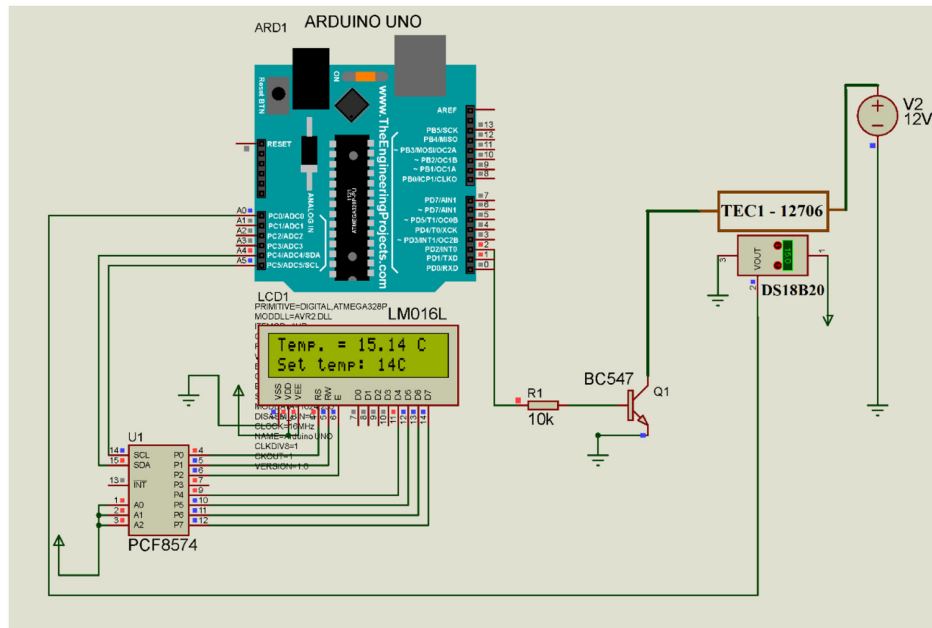
pin may supply less than five volts, and the board may be unstable. Using more than 12 V, the voltage regulator may overheat and damage the board. The recommended range is 7–12 volts. Thermoelectric coolers are composed of N and P-type semiconductors connected by metal contacts to produce a junction that can cool one side while heating the other. Electrons passing from a low energy level in a p-type semiconductor material absorb heat on the cool side (Vasant et al., 2017). The power source supplies the energy to drive electrons across the system. As electrons travel from n-type to p-type, the hot side energy is removed via the heat sink. The DS18B20 is a programmable temperature sensor that only requires a single wire to operate. It has an accuracy of 1°C and can measure temperatures across an extensive range, from -55°C to +125°C (Koestoer et al., 2019). The circuit diagram for the Arduino-based temperature controller is shown in Figure 4, designed and simulated in Proteus virtual system modelling (VSM) (Yaqoob & Obed, 2019). In this circuit, a temperature sensor (DS18B20) is connected to pin A0 of the Arduino. The temperature sensor output is converted to a digital signal by analog-to-digital converter in the Arduino; then, this digital value is compared to a set value. If the temperature exceeds the set value, Arduino turns ON the thermoelectric cooler through the digital output pin 2. As the thermoelectric cooler takes ~3A current, it may damage the output pin of the microcontroller. Therefore, the thermoelectric cooler is separated from the microcontroller through a BC547. The microcontroller sends a signal to BC547 to turn ON the thermoelectric cooler as the temperature overshoots the set value. The controller turns OFF the thermoelectric cooler when the temperature falls below the set temperature. Furthermore, the temperature values are also displayed on an LCD connected to the controller. The set temperature can be changed by modifying the set temperature value in the Arduino code.

5. Characterization of the Laser Diode with Cooling System

The design of the complete laser diode system with its driver circuit and microcontroller-based cooling system is shown in Figure 5, simulated in Proteus VSM (Yaqoob & Obed, 2019).

Figure 6 shows the experimentally acquired results of the laser diode with a microcontroller-based cooling system. The graph (Figure 6(a)) shows the cooling system's efficiency. The data plotted in Figure 6(a) are recorded when the laser diode was operational to analyze the cooling system efficiency and check that the cooling system is efficient enough to extract the heat and reduce the temperature. The cooling system is efficient enough to control the temperature of the laser diode; as it can be seen from the graph, the microcontroller-based cooling system brings down the temperature of the laser diode from 23°C to the set temperature of 14°C in less than 4 minutes (Naeem et al., 2022a).

Figure 6(b) shows the effect of the laser diode temperature (red) on the output power (black) if the laser diode is operated for an extended period with the microcontroller-based cooling system. The temperature of the laser diode remains stable (around 16°C) for an extended period of operation as the cooling system is working efficiently. The laser diode's power (black line) remains constant throughout the period. The temperature variation is very small, about 1°C, but the power remains stable. As a result, the output power of the laser diode is now durable. By comparing graphs (Figures 3(b) and 6(b)), with a microcontroller-based cooling system, the laser diode works more efficiently, and it can be operated for an extended period without any power losses. The proposed design seems promising in reducing the damaging probability of the laser diode.

Figure 5
Microcontroller-based cooling system with laser diode driver circuit
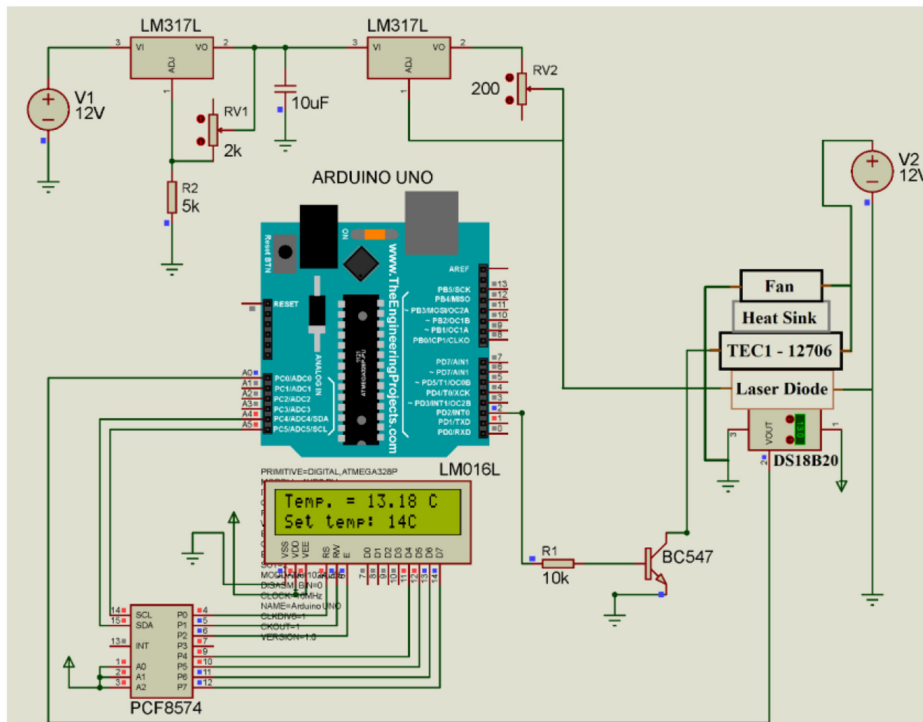
Figure 6
(a) Efficiency of cooling system to decrease the laser diode temperature with time.
(b) Variation in laser diode output power and temperature along time
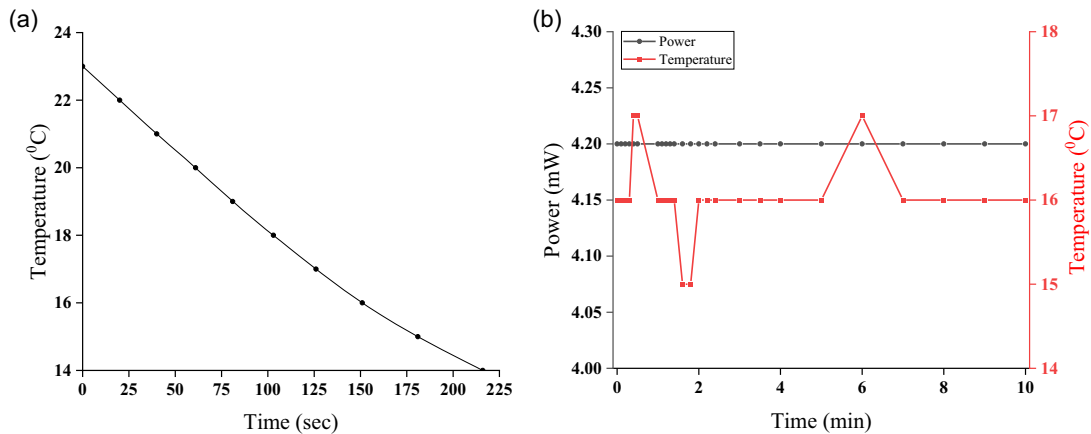
6. Conclusion

Design and fabrication of a stable prototype laser diode system, along with its driver circuit and microcontroller-based thermoelectric cooling system, are carried out in this work. The driver circuit consisting of voltage and current control is designed and simulated to control the output power of the laser diode. The temperature of the laser diode increases rapidly when operated continuously. The laser diode output power decreases due to temperature rise during the extended period of operation. To maintain the temperature of the laser diode, a microcontroller-based thermoelectric cooling system is designed and constructed using a thermoelectric cooler. The temperature sensor detects the temperature change and sends the signal to the microcontroller; the microcontroller turns ON the cooling system to extract the heat produced during the lasing action. The laser diode temperature remains constant as the excess heat is removed using a microcontroller-based cooling system. It works more efficiently and can be operated for an extended period without any power losses. The damaging probability of the crystal because of temperature and current overflow also decreases with the proposed cooling system design.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

The data supporting this study's findings are available within the article [and its supplementary material].

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