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Voltage - Current (I–V) Characteristics of 532 nm and 650 nm Semiconductor Lasers at Varying Optical Output Powers

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ABSTRACT

This study investigates the current-voltage (I-V) characteristics of 532 nm and 650 nm semiconductor laser diodes at multiple optical power levels (5–200 mW). A systematic experimental approach revealed distinct electrical behaviors, with threshold voltages ranging from 1.5 to 2.0 V. Lower-power lasers (50 mW for 532 nm and 100 mW for 650 nm) exhibited current saturation, reaching maxima of 225 mA and 183 mA, respectively. Higher-power lasers (200 mW) showed near-linear I-V characteristics, with 532 nm lasers achieving up to 829 mA at 4V, while 650 nm reached 384 mA. The 650 nm lasers generally displayed lower threshold voltages, while the 532 nm lasers showed more pronounced saturation. These insights are vital for designing efficient driver circuits and optimizing the performance of semiconductor lasers in optical communication and photonic systems. These findings support the design of efficient driver circuits and contribute to improved performance of semiconductor lasers in photonic and optoelectronic systems.

KEYWORDS: *Current-voltage (I-V) characteristics, Laser driver optimization, Optical power levels, Semiconductor laser diodes, Threshold voltage, Wavelength dependence*

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1. INTRODUCTION

Semiconductor lasers play a critical role in a broad range of applications, including optical communication, spectroscopy, materials processing, biomedical imaging, and consumer electronics. Their compact size, high efficiency, and spectral purity make them ideal candidates for integration into both industrial and research systems. However, ensuring stable and efficient operation remains a technical challenge, particularly in thermal management, mode stability, and consistent output under varying electrical conditions.

A fundamental step in optimizing laser diode performance lies in understanding their electrical behavior, specifically, the current-voltage (I-V) characteristics. These characteristics are essential for evaluating the threshold conditions, electrical efficiency, and dynamic response of the devices. While numerous advances have been made in laser diode design through innovations in materials and fabrication techniques [1–3], a detailed understanding of how I–V behavior varies with optical output power is still needed. This is particularly important for improving driver circuit design, managing thermal effects, and extending device lifetime.

Prior studies have extensively explored the structural and electrical features of semiconductor lasers. Research has focused on device architectures such as quantum wells and strained-layer superlattices, as well as on material systems like GaAs/AlGaAs and InP-based compounds. For instance, investigations into GaAs/AlGaAs quantum cascade lasers and their temperature-dependent performance have contributed valuable insights into thermal effects on lasing efficiency [4–6]. Al-Marhaby et al. reported on the I-

V characteristics of InP/AlGaInP quantum dot lasers across a wide temperature range, highlighting their thermal sensitivity and structural dependence [7]. More recent work emphasizes material innovations to improve efficiency. Bhattarai et al. (2024) examined the advantages of GaN-based laser diodes in enhancing heat management and power delivery [8], while Wang et al. (2024) explored drive current modulation strategies in tunable external cavity lasers for high-speed optical communication [9].

Despite these contributions, a specific knowledge gap remains: the influence of optical output power levels on the I–V characteristics of visible semiconductor lasers, particularly for commonly used wavelengths such as 532 nm (green) and 650 nm (red), has not been sufficiently characterized. Understanding this relationship is crucial for selecting the appropriate laser for a given application and for designing efficient, application-specific driver circuitry.

A summary of application suitability based on electrical behavior is summarized in Table (1) hereunder.

Table 1: Application Suitability Based on Electrical Behavior

532 nm lasers		650 nm lasers		
50–100 mW	**200 mW**	**5 mW**	**100 mW**	**200 mW**
Ideal for applications needing stable but moderate power. e.g., laser alignment and microscopy.	Suitable for high-power uses like fluorescence excitation and light-induced diagnostics.	Well-suited for barcode scanners and indicators.	Effective for optical data systems such as DVDs	Applicable in therapeutic lasers and precision marking systems.

2. Materials and Methods

This study aims to address this gap by experimentally investigating the I–V behavior of 532 nm and 650 nm semiconductor laser diodes at multiple optical power levels (5–200 mW). These two wavelengths are widely used in biomedical imaging, optical storage, alignment systems, and display technologies. Green lasers, for example, are especially valuable due to their high visibility and strong absorption in biological tissues, while red lasers are essential in consumer electronics such as DVD players and barcode scanners. By analyzing how electrical characteristics evolve with changes in optical power output, this work provides valuable insights that support the effective design, control, and application of visible semiconductor lasers in diverse photonic systems.

The experimental setup utilized a programmable DC power supply (KEYSIGHT E36313A, made in USA) and a digital multimeter (KEYSIGHT 34470A, made in USA) to investigate the voltage-current characteristics of semiconductor lasers. Six different semiconductor lasers were studied, varying in wavelength (532 nm and 650 nm) and optical power (5 mW, 50 mW, 100 mW, and 200 mW).

The digital multimeter was connected in series with each laser diode and then connecting this combination in parallel with the programmable DC power supply. For each semiconductor laser, the Voltage was increased from 0 V to 4 V in 0.1 V steps. The corresponding electrical current was recorded at each voltage step using the digital multimeter.

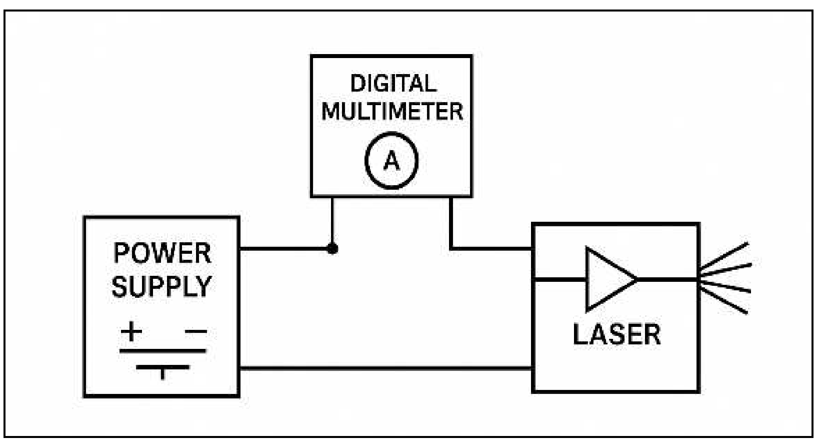

Fig. 1: Schematic diagram of the experimental setup for measuring the I–V characteristics of laser diodes using a power supply and digital multimeter.

The semiconductor lasers used in this study are characterized in Table 2.

Table 2: Specifications of the semiconductor lasers used in the study

Semiconductor Laser	Wavelength (nm)	Optical Power(mW)
1	532	200
2	532	100
3	532	50
4	650	200
5	650	100
6	650	5

3. Results

The voltage–current (I–V) characteristics of the semiconductor lasers were systematically measured and recorded. The data for the 532 nm lasers at different optical power levels are summarized in Table 3 and illustrated in Figure 2.

Table 3: Current measurements for 532 nm semiconductor lasers at different optical powers

Voltage (V)	Current (mA) 532 nm, 200 mW	Current (mA) 532 nm, 100 mW	Current (mA) 532 nm, 50 mW
0	0	0.017	0
0.1	0	0.022	0.005
0.2	0	0.025	0.011
0.3	0	0.03	0.012
0.4	0	0.038	0.014
0.5	0	0.041	0.02
0.6	0	0.044	0.021
0.7	0	0.049	0.028
0.8	0	0.054	0.029
0.9	0	0.062	0.035
1	0	0.065	0.051
1.1	0	0.073	0.086
1.2	0	0.092	0.157
1.3	0.02	0.129	0.332
1.4	0.19	0.192	0.51
1.5	1.3	0.253	0.578
1.6	8.5	0.295	0.607
1.7	27	0.322	0.64
1.8	53	0.366	1.187
1.9	84	1.106	9.94
2	117	9.49	37
2.1	152	34	82
2.2	187	74	152
2.3	224	119	190
2.4	261	171	198
2.5	298	226	206
2.6	336	286	215
2.7	373	317	222
2.8	410	326	226
2.9	447	326	226
3	483	326	226
3.1	520	326	225
3.2	556	327	225
3.3	591	327	225
3.4	626	327	225
3.5	661	327	225
3.6	695	327	225
3.7	728	327	225

3.8	762	327	225
3.9	796	327	225
4	829	327	225

This result is illustrated graphically as shown in Figure (2) below.

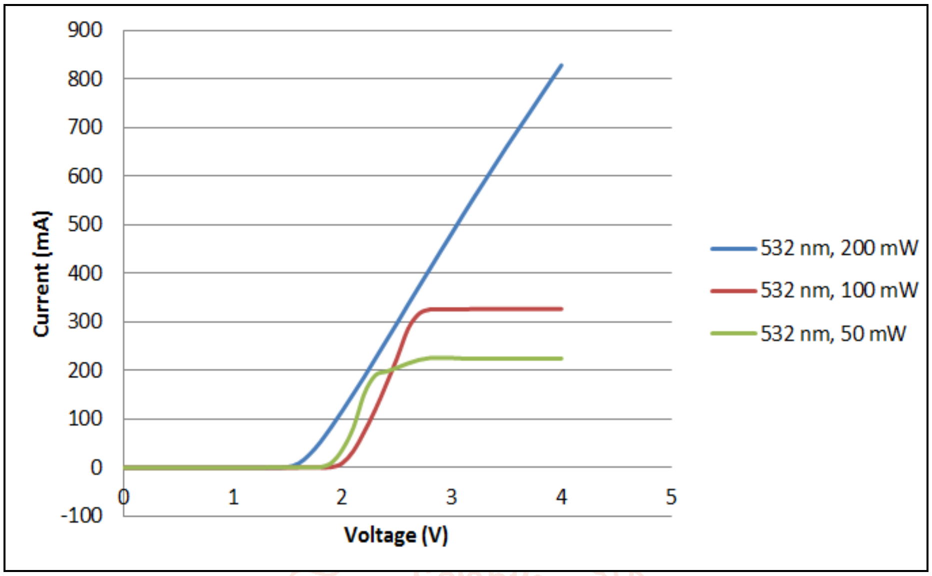

Fig. 2: I–V characteristics of 532 nm lasers showing saturation in lower power devices (50 mW, 100 mW) and linearity at 200 mW

As shown in Table (3) and Figure (2), the 532 nm laser diodes exhibited distinct electrical behavior depending on their optical output power. The 200 mW laser demonstrated a near-linear I–V relationship beyond threshold, reaching 829 mA at 4 V. In contrast, the 100 mW and 50 mW lasers exhibited saturation behavior, with current plateauing at approximately 327 mA and 225 mA, respectively, despite increasing voltage.

Similarly, the 650 nm lasers displayed power-dependent characteristics. The 200 mW laser maintained a consistent linear I–V trend across the voltage range, while the 100 mW laser reached saturation near 183 mA. The 5 mW laser demonstrated minimal current draw, with limited current increase throughout the voltage range, indicating reduced electrical-to-optical efficiency.

Table 4: Current measurements for 650 nm semiconductor lasers at different optical powers

Voltage (V)	Current (mA) 650 nm, 200 mW	Current (mA) 650 nm, 100 mW	Current (mA) 650 nm, 5 mW
0	0	0.005	0.014
0.1	0.005	0.013	0.017
0.2	0.006	0.022	0.018
0.3	0.007	0.03	0.018
0.4	0.01	0.036	0.019
0.5	0.009	0.043	0.02
0.6	0.011	0.049	0.019
0.7	0.01	0.06	0.019
0.8	0.011	0.068	0.018
0.9	0.011	0.081	0.019
1	0.008	0.106	0.017
1.1	0.011	0.149	0.017
1.2	0.013	0.21	0.016
1.3	0.014	0.307	0.017
1.4	0.015	0.427	0.017
1.5	0.014	0.544	0.018
1.6	0.058	0.648	0.032
1.7	0.508	0.746	0.075
1.8	2.716	0.885	0.253

1.9	9.64	2.34	0.737
2	20.4	11.5	1.414
2.1	33	28	2.17
2.2	47	47	2.968
2.3	62	67	3.79
2.4	77	87	4.629
2.5	93	107	5.48
2.6	109	127	6.34
2.7	125	147	7.208
2.8	142	169	8.082
2.9	159	181	8.963
3	176	181	9.854
3.1	184	182	10.767
3.2	212	182	11.682
3.3	230	182	12.6
3.4	248	182	13.5
3.5	267	183	14.4
3.6	287	183	15.35
3.7	308	183	16.272
3.8	331	183	17.193
3.9	357	183	18.118
4	384	183	19.05

Figure (3) below is a graphical representation of the results arranged in table (2).

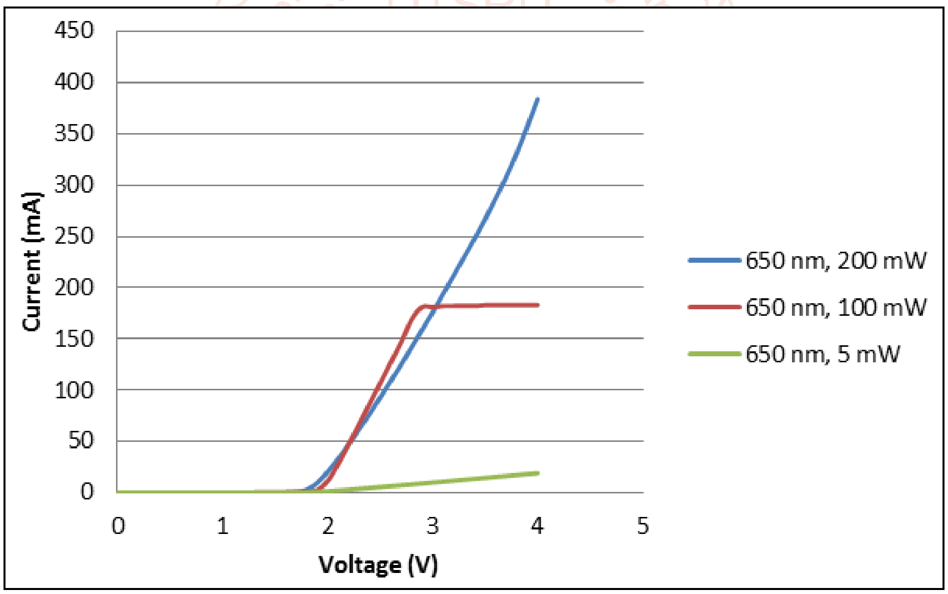

Fig. 3: Current-Voltage (I-V) Characteristics of 650 nm Semiconductor Lasers at Various Optical Power Levels (5 mW, 100 mW, 200 mW)

The voltage-current characteristics exhibited distinct behavior patterns for each laser configuration. For the 532 nm laser with 200 mW optical power, the relationship between voltage and current was approximately linear from 1.6 volts to 4 volts, with the current reaching 829 mA at maximum voltage. The threshold voltage for this laser was around 1.3-1.5 volts, after which the current began to increase significantly.

For the 532 nm laser with 100 mW optical power, the current increased rapidly between 1.9 and 2.7 volts, reaching a plateau at approximately 327 mA for voltages above 2.8 volts. This indicates a saturation behavior where further voltage increases did not produce substantial increases in current.

The 532 nm laser with 50 mW optical power showed a steep current increase between 1.9 and 2.3 volts, with current stabilizing at approximately 225 mA for voltages above 2.8 volts. This saturation occurred at a lower current level compared to the higher-power 532 nm lasers.

The 650 nm lasers displayed different characteristics. The 650 nm laser with 200 mW optical power exhibited a nearly linear voltage-current relationship from 2 volts to 4 volts, reaching 384 mA at maximum voltage. Unlike the 532 nm lasers, it did not display saturation behavior within the tested voltage range.

The 650 nm laser with 100 mW optical power showed rapid current increase between 1.9 and 2.9 volts, reaching saturation at approximately 183 mA for voltages above 3 volts. The 650 nm laser with 5 mW optical power demonstrated an approximately linear relationship between voltage and current from 2 volts to 4 volts, achieving a maximum current of 19.05 mA.

The operational voltage for all semiconductor lasers tested was determined to be 3 volts, representing an optimal voltage for standard operation across the different configurations.

Figure (4) presents the combined I–V characteristics for both 532 nm and 650 nm lasers at varying optical power levels. The plot clearly shows differences in threshold voltages, saturation effects, and current handling between the different configurations, illustrating the influence of both wavelength and power on electrical behavior.

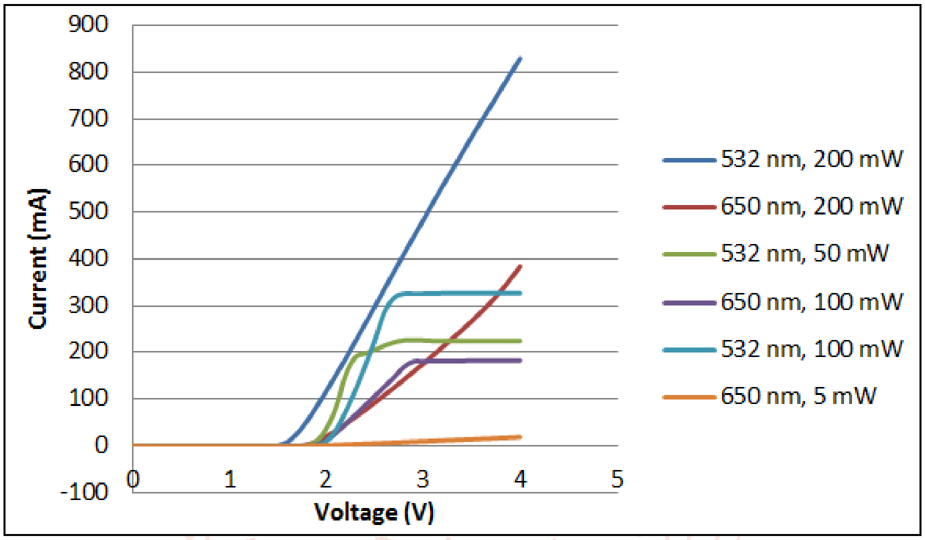

Fig. 4: Combined I–V characteristics of 532 nm and 650 nm laser diodes at varying optical power levels (5 mW, 50 mW, 100 mW, and 200 mW).

4. Discussion

This study offers a detailed analysis of the voltage–current (I–V) characteristics of 532 nm and 650 nm semiconductor lasers operating at varying optical power levels. The results demonstrate distinct threshold behavior, linearity in high-power devices, and saturation effects in lower-power configurations. These trends align with established laser diode models and corroborate findings from previous research, such as those reported by Al-Marhaby et al. [7].

As shown in Figures 2 and 3, both laser types exhibit a clear threshold voltage in the range of 1.5 to 2.0 V, consistent with standard values for visible laser diodes [10]. Below this threshold, current remains negligible; above it, a rapid current increase indicates the onset of lasing action.

The 200 mW laser exhibits a nearly linear increase in current beyond threshold, suggesting efficient carrier injection and stable dynamic resistance. In contrast, the 100 mW and 50 mW lasers display current saturation, particularly evident in the 50 mW device, where current plateaus are at a lower level. This behavior is likely due to thermal effects, increased non-radiative recombination, or carrier leakage.

Similar behavior is observed in the 650 nm lasers. The 200 mW laser shows a linear post-threshold I–V curve, while the 100 mW device demonstrates mild saturation. The 5 mW laser remains low in current across the voltage range, indicating lower efficiency and limited output.

Figure 4 enables direct comparison across devices. High-power lasers (200 mW) at both wavelengths show steep, linear post-threshold I–V curves, indicative of efficient electrical-to-optical conversion. In contrast, lower-power lasers, particularly the 532 nm (50 mW) and 650 nm (5 mW), reach saturation more quickly, suggesting limited current-handling capacity and thermal constraints. Slightly lower threshold voltages observed in 650 nm lasers likely result from differences in material systems.

Saturation in lower-power devices arises from Joule heating, Spatial hole burning, Carrier leakage, and Linearity in higher-power lasers.

The observed differences between 532 nm and 650 nm devices stem from their active region materials. Green lasers (532 nm) use InGaN/GaN with a wider bandgap (~2.4 eV), necessitating higher threshold voltages. Red lasers (650 nm), typically based on AlGaInP (bandgap ~1.9 eV), achieve lasing at lower voltages, influencing their I–V response.

Saturation behavior in lower-power lasers has implications for device lifetime and reliability. Poor thermal management can lead to Increased defect formation, Facet degradation, and contact degradation.

Shockley diode equation describes carrier injection below threshold, it does not account for gain saturation, stimulated emission, or refractive index changes above threshold. A more accurate description is provided by laser rate equations.

While this study primarily focuses on experimental characterization, the observed I–V behaviors are qualitatively consistent with predictions from laser rate equations. These models explain threshold behavior, saturation, and efficiency variations. Future work may include fitting experimental data to steady-state solutions of these equations to extract parameters such as gain coefficient, carrier lifetime, and internal optical loss.

5. Conclusions

This study investigated the voltage–current (I–V) characteristics of 532 nm (green) and 650 nm (red) semiconductor laser diodes across a range of optical output powers (5–200 mW). All devices exhibited a distinct threshold voltage of 1.5 to 2.0 V, necessary for initiating lasing action. High-power lasers (200 mW) demonstrated a nearly linear I–V relationship beyond the threshold, indicative of efficient carrier injection and thermal handling. In contrast, lower-power lasers (50 mW and 100 mW for 532 nm; 100 mW for 650 nm) exhibited saturation behavior, where voltage increases resulted in diminished current response, reflecting limited current-handling capacity and possible thermal limitations. Notably, the 650 nm lasers exhibited slightly lower threshold voltages compared to their 532 nm counterparts, consistent with material differences—namely, the use of AlGaInP for red lasers and InGaN/GaN for green lasers. The lowest-power laser (650 nm, 5 mW) displayed minimal current draw, suggesting reduced efficiency and limited suitability for high-demand applications. These findings provide valuable insight into the relationship between electrical behavior and optical power for visible semiconductor lasers. They support more effective driver circuit design and informed selection of laser diodes based on application-specific power and thermal requirements.

Future work may focus on quantitatively modeling these behaviors using laser rate equations to extract internal parameters such as gain coefficient, carrier lifetime, and optical loss, contributing to more predictive device modeling and system integration.

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Conflicts of Interest

The authors declare that they have no known conflicts of interest regarding the publication of this paper. All research was conducted without any financial, personal, or professional relationships that could be construed as influencing the work.

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