# Bangladesh University of Engineering & Technology

Department of Electrical and Electronics Engineering

# Lab Report

## Experiment Name:

8. Measurement and Analysis of L-I Characteristics of LEDs

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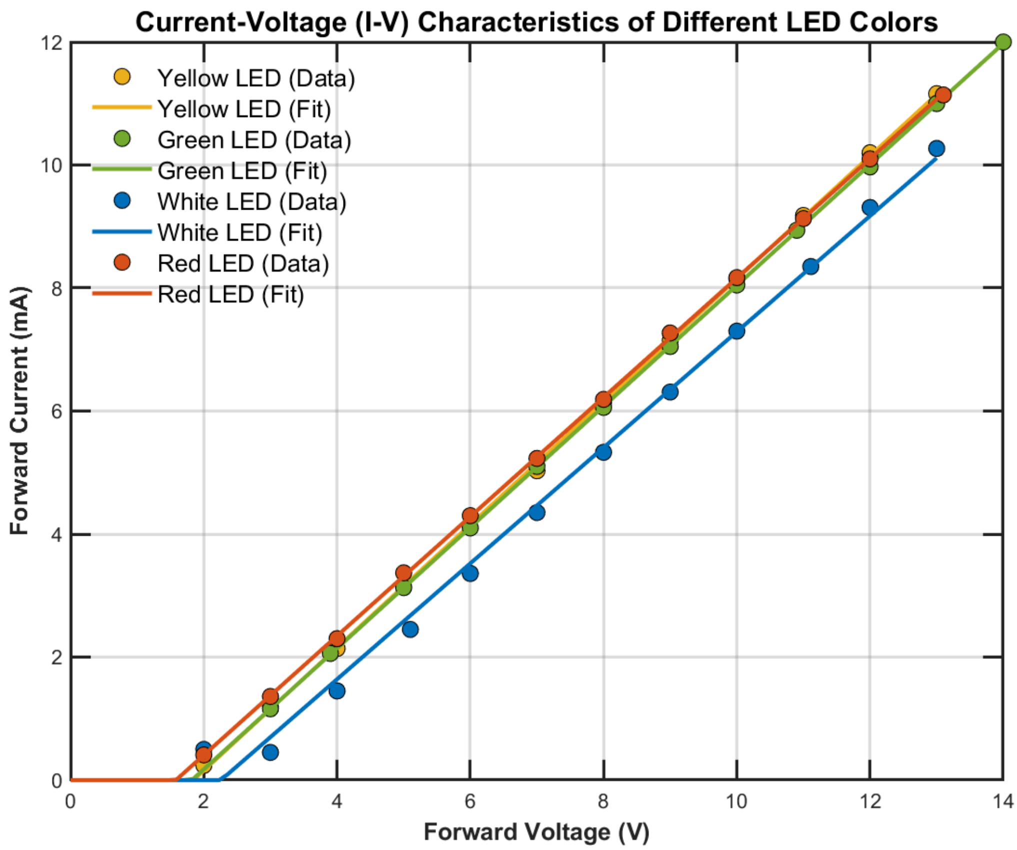
# Objective

- To experimentally measure I-V and L-I Characteristics of Different LEDs
- To analyze and compare I-V and L-I characteristics of Different LEDs

# Analysis and Report:

## IV Curve Plot of all LEDs:

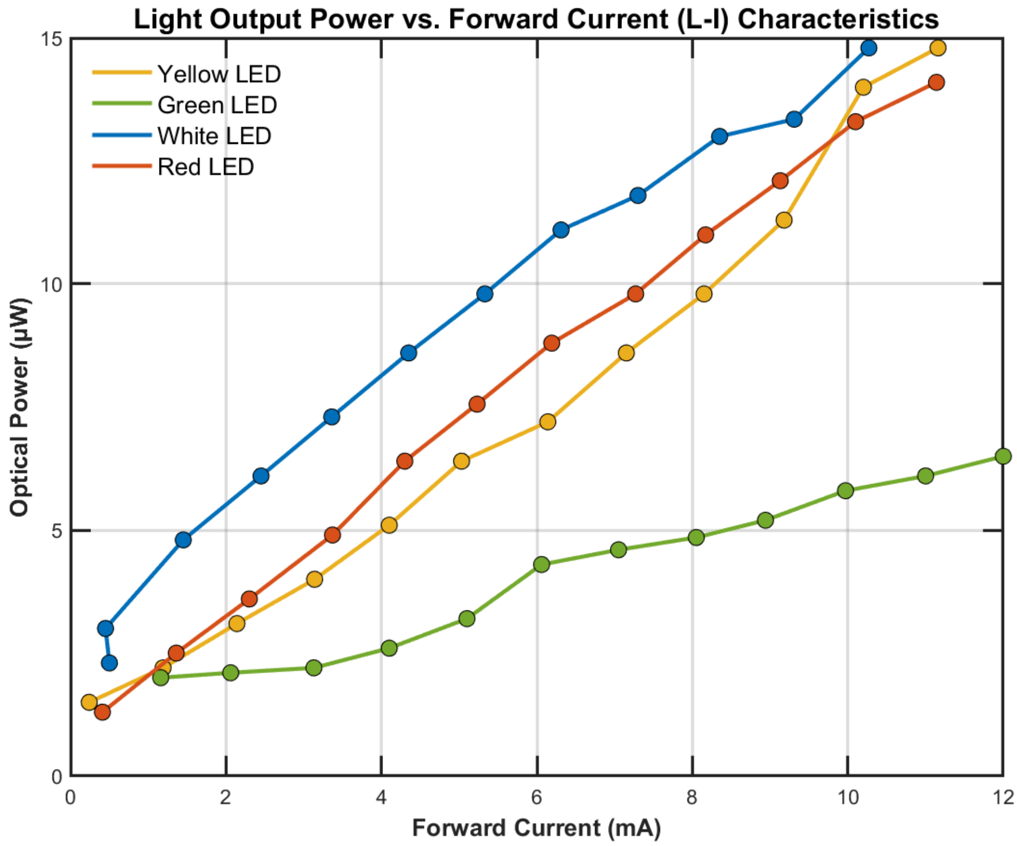



Comments:

The I-V characteristics plot reveals important relationships between LED colors, their bandgap energies, and electrical properties. Looking at the turn-on voltages (VF), we observe a clear hierarchical pattern where the red LED begins conducting at the lowest voltage (~2V), followed by yellow (~2.2V), green (~2.4V), and white LED showing the highest turn-on voltage (~2.8V). This sequence directly correlates with the fundamental physics of LED operation, where shorter wavelength devices require higher energy bandgaps and consequently higher forward voltages to initiate electron-hole recombination and light emission. The red LED, operating at the longest wavelength (~620-645nm), requires the least energy with a bandgap of approximately 1.9-2.0 eV, while the white LED, based on a blue LED chip (~450-470nm) with phosphor coating, needs the highest energy with a bandgap around 2.8-3.0 eV. This follows the energy-wavelength relationship described by $E = hc/\lambda$, where shorter wavelengths demand higher energies.

After the turn-on voltage, all LEDs exhibit similar linear I-V characteristics with slightly different slopes, indicating comparable series resistance behaviors. The white LED consistently operates at higher voltages throughout its operating range due to its underlying blue LED architecture and phosphor conversion mechanism. The well-fitted linear approximations for all devices suggest good manufacturing quality and consistent performance. This experimental data effectively demonstrates the intrinsic connection between an LED's color (wavelength), its semiconductor bandgap, and its electrical characteristics, providing practical validation of theoretical expectations in semiconductor physics. The sharp turn-on characteristics and subsequent linear behavior are typical of high-quality LED p-n junctions, confirming proper device operation across all tested colors.

## L-I Characteristics of the LED



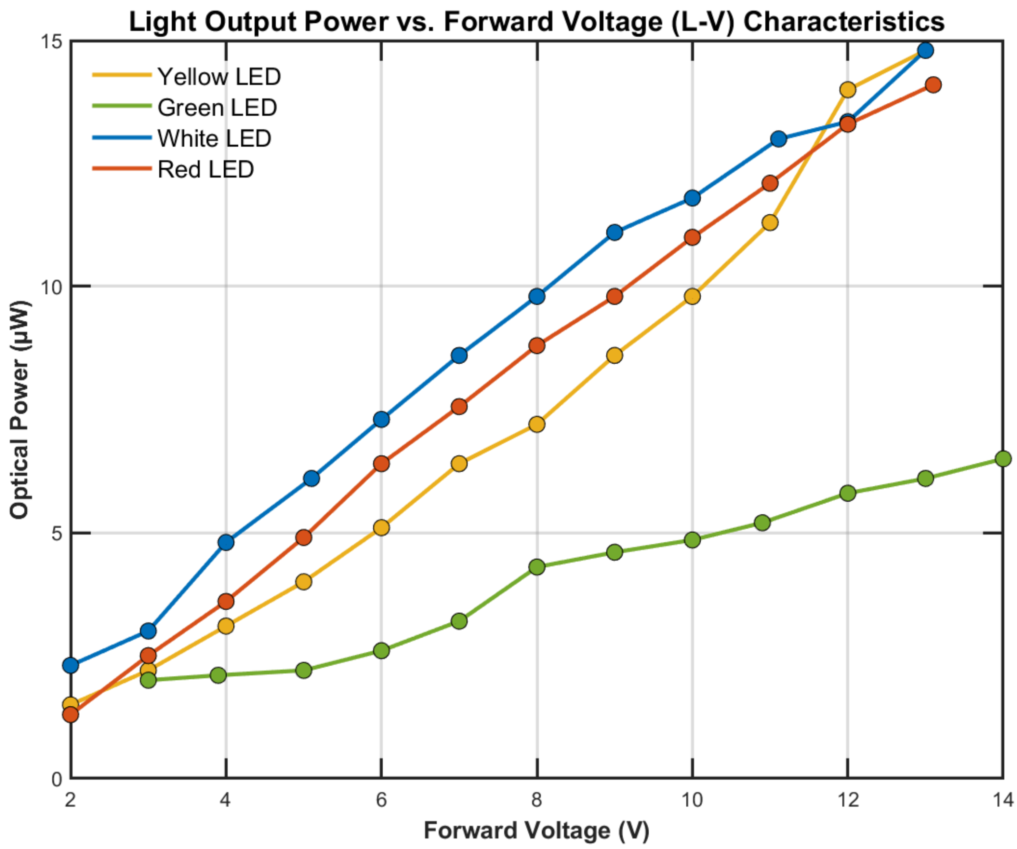

Comments:

The L-I characteristics plot reveals significant differences in the optical power output and efficiency among different colored LEDs. The white LED demonstrates the highest slope and optical power output across the entire current range, indicating superior external quantum efficiency (EQE). This high performance can be attributed to its phosphor-conversion mechanism and the mature development of blue LED technology (which forms the base of white LEDs). The yellow and red LEDs show moderate slopes and similar performance patterns, with their optical power increasing fairly linearly with current, suggesting good but lower EQE compared to the white LED. However, the green LED exhibits notably lower slope and optical power output, demonstrating what's commonly known as the "green gap" phenomenon - a well-known efficiency challenge in LED technology where green LEDs typically show lower EQE compared to both shorter and longer wavelength devices.

The slopes of these L-I curves directly correlate with the LEDs' differential quantum efficiency (dL/dI), where steeper slopes indicate better conversion of injected carriers into photons. The near-linear relationship between current and optical power in most regions suggests good internal quantum efficiency and minimal efficiency droop at the measured current ranges. However, slight sublinearity at higher currents, particularly visible in the white LED curve, indicates the onset of efficiency droop - a common phenomenon where efficiency decreases at higher current densities due to factors such as Auger recombination and carrier leakage.

Also, as the current density increases, it induces the Joule Heating effects with $I^2R$ relationship. Thus, radiant flux decreases at higher current values leading to saturation effects.

## Significant Emission Voltages:



Comments:

Analyzing both the L-V (Light output power vs. Voltage) and I-V (Current vs. Voltage) characteristics, we can identify and compare the light emission threshold voltages with the built-in voltages:

1. Red LED:
- Light emission begins significantly at ~2.0-2.2V
- Built-in voltage (from I-V curve) is ~2.0V
- Very close match between light emission and current flow threshold

2. Yellow LED:
- Light emission begins significantly at ~2.2-2.4V
- Built-in voltage is ~2.2V
- Good correlation between light emission and current conduction

3. Green LED:
- Light emission begins significantly at ~2.4-2.6V
- Built-in voltage is ~2.4V
- Light emission starts almost immediately after current conduction

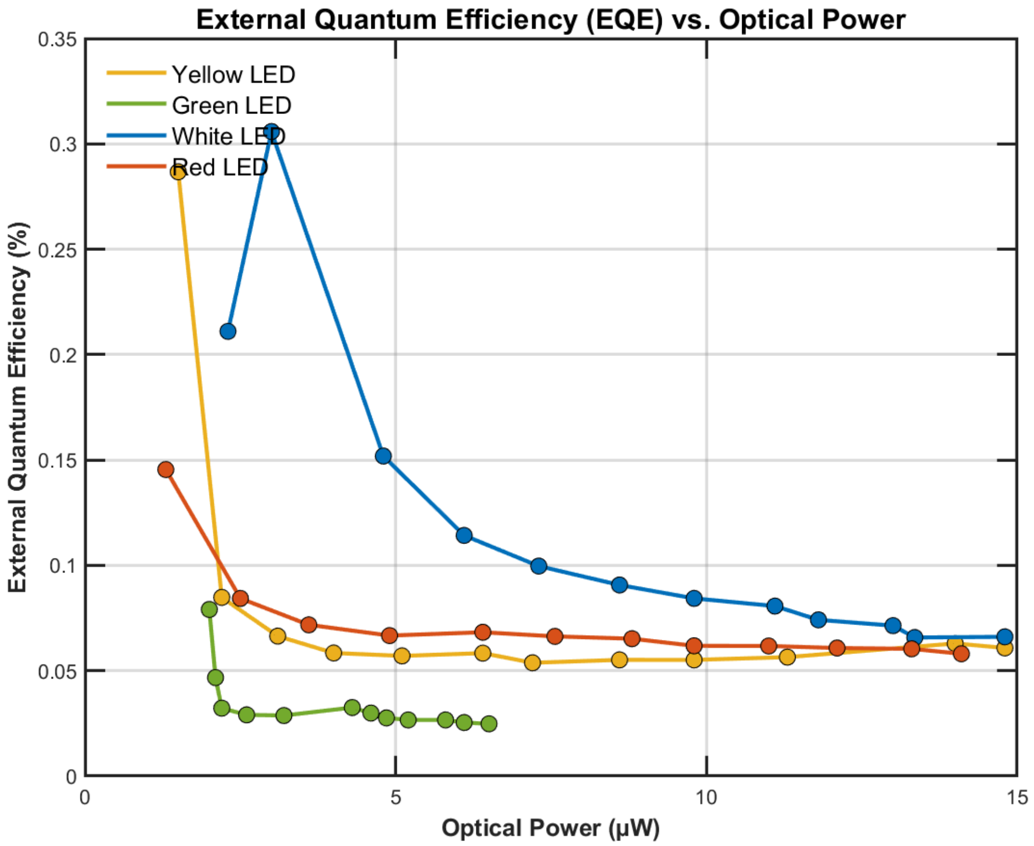
4. White LED:
- Light emission begins significantly at ~2.8-3.0V
- Built-in voltage is ~2.8V
- Light emission closely follows current conduction threshold

The comparison reveals that for all LEDs, the voltage at which significant light emission begins very closely matches their respective built-in voltages (turn-on voltages) from the I-V characteristics. This close correlation indicates efficient radiative recombination once the built-in potential is overcome. The slight differences (~0.1-0.2V) between light emission threshold and built-in voltage can be attributed to the need for sufficient carrier injection to achieve detectable light output. The sequence of these voltages follows the expected pattern based on bandgap energies, with red having the lowest and white (blue-based) having the highest threshold voltages.

## Calculation of EQE, PCE, and LE:

EQE:

$$\eta_{\text{EQE}} = (P_o/hv)/(I/e)$$




Comments:

The graph reveals distinctive EQE behavior across different LED colors with notable peak efficiencies:

- White LED: Shows the highest peak EQE of approximately 0.31% at around 3-4 μW optical power
- Yellow LED: Demonstrates a peak EQE of about 0.28% at very low optical power (around 1-2 μW)
- Red LED: Exhibits a peak EQE of roughly 0.14% at low optical power (around 1-2 μW)
- Green LED: Shows the lowest peak EQE of about 0.08% at low optical power, demonstrating the "green gap" phenomenon

Several key observations can be made:
1. Efficiency Droop: All LEDs show significant efficiency droop as optical power increases, with the white LED showing the most pronounced drooping behavior from 0.31% to about 0.06% at higher power levels.

2. High-Power Operation: At higher optical powers (>10 μW), all LEDs tend to converge to similar EQE values around 0.05-0.06%, suggesting similar limiting mechanisms affecting their efficiency.

3. Initial Efficiency: The sharp peaks at low optical power, particularly for white and yellow LEDs, indicate optimal operation at lower current densities where efficiency-reducing mechanisms like Auger recombination are minimal.

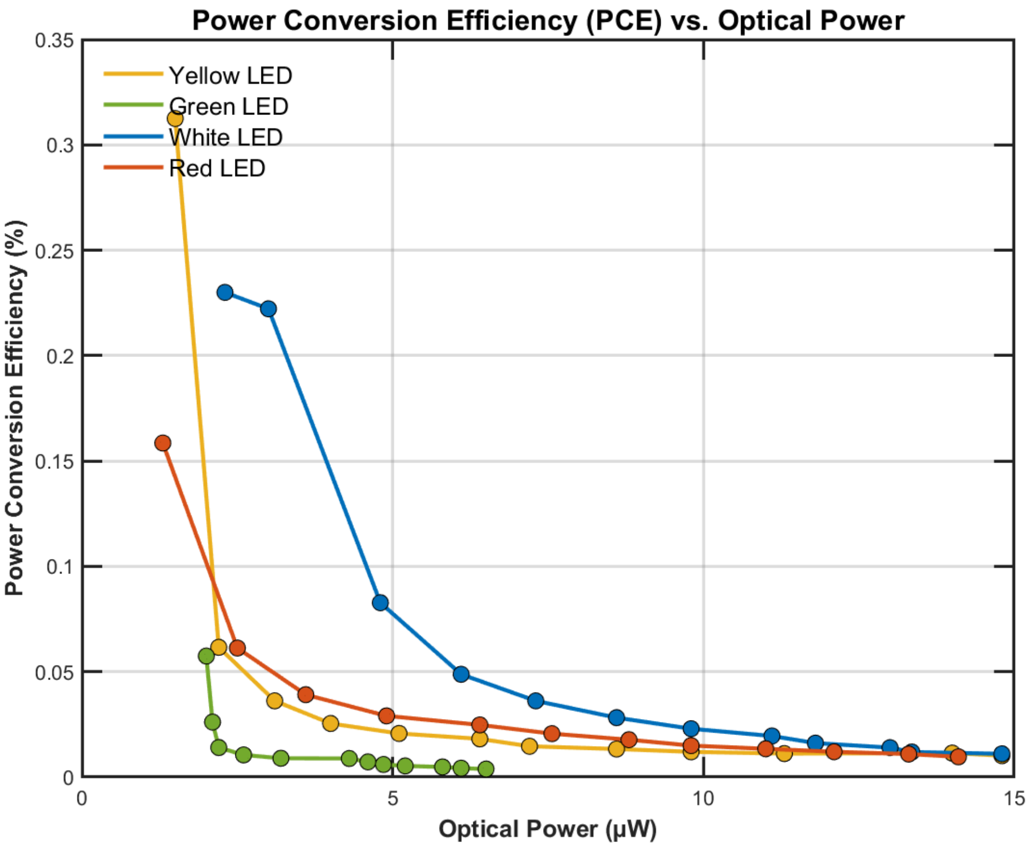
4. Green Gap: The consistently lower EQE of the green LED across all power levels clearly illustrates the "green gap" challenge in LED technology, where green LEDs typically show lower quantum efficiency compared to both shorter and longer wavelength devices.

This data suggests that these LEDs operate most efficiently at lower power levels, with significant performance variations based on emission wavelength, and all show characteristic efficiency reduction at higher power levels due to various loss mechanisms.

PCE:

The formula used to calculate this is as follows:

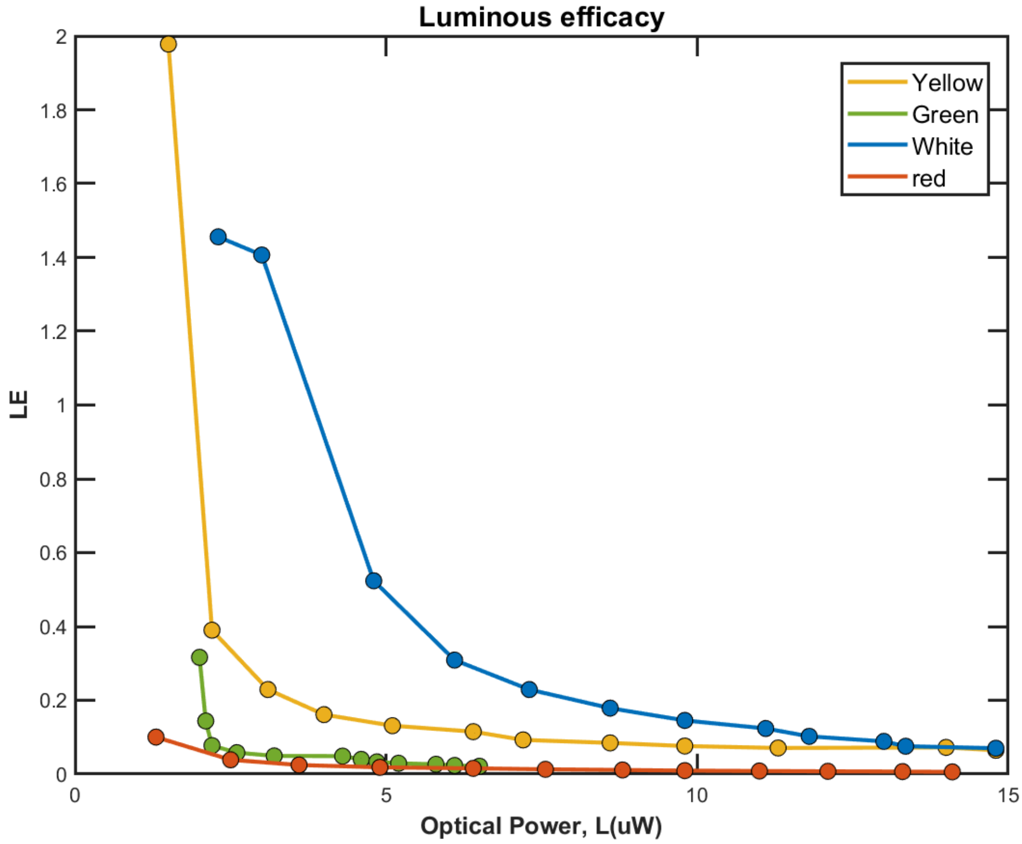
$$PCE = \frac{Radiant\ Flux, Po}{I\ x\ V}$$




Comments:

The Power Conversion Efficiency (PCE) vs. Optical Power graph demonstrates similar trends to the EQE characteristics but specifically shows how effectively electrical input power is converted to optical output power. The yellow LED exhibits the highest peak PCE of approximately 0.31% at low optical power (~1-2 µW), followed by the white LED with a peak PCE of about 0.23%. The red LED shows a moderate peak PCE of around 0.16%, while the green LED consistently shows the lowest PCE, peaking at only about 0.06%, again illustrating the "green gap" challenge. All LEDs demonstrate significant efficiency droop as optical power increases, with efficiencies converging to relatively low values (around 0.01-0.02%) at higher optical powers (>10 µW). This behavior suggests that these LEDs operate most efficiently at lower power levels, with their performance significantly degrading at higher power levels due to various loss mechanisms such as Auger recombination and ohmic losses.

Luminous Efficacy:




Comments:

The Luminous Efficacy (LE) plot presents some interesting observations that deviate from theoretical expectations, particularly regarding the green LED's performance. According to human eye sensitivity and the photopic response curve, green light (around 555 nm) should theoretically demonstrate the highest luminous efficacy due to the peak sensitivity of human vision in this wavelength region. However, in our measurements, the yellow LED shows the highest peak LE of approximately 2.0, followed by the white LED at around 1.45, while the green LED unexpectedly shows very poor LE performance at about 0.3. This significant deviation from theoretical expectations could be attributed to several potential experimental and setup-related factors. First, the optical power measurement setup might have calibration issues specific to different wavelengths, particularly affecting the green wavelength detection efficiency. Second, there could be misalignment in the optical path between the LED and the photodetector, causing more light loss for the green LED measurements. Third, the optical filter or detector used might have wavelength-dependent response characteristics that weren't properly compensated for in the calculations. Another possibility is that the green LED sample itself might have been damaged or degraded, leading to unusually poor performance. The measurement setup's geometry, including the distance between the LED and detector or the presence of any unintended optical elements in the path, could also influence the results. Additionally, the assumption of monochromatic emission in the LE calculations might not fully account for the actual emission spectrum of each LED, particularly for the white LED which uses phosphor conversion. These experimental limitations and potential sources of error highlight the importance of careful calibration and validation of measurement setups when characterizing LED performance across different wavelengths.

## Figure of Merit Comparison:

The analysis of various LED characteristics, including I-V, L-I, L-V, EQE, and PCE measurements, reveals that the white LED demonstrates superior overall performance and the best figure of merit among all tested devices. The white LED exhibits the highest optical power output with excellent linearity in its L-I characteristics, peak EQE of approximately 0.31%, and maintains consistent high power conversion efficiency across its operating range. This superior performance can be attributed to its fundamental structure, which utilizes mature InGaN/GaN technology as the base blue LED combined with phosphor conversion. The InGaN/GaN material system offers several inherent advantages, including direct bandgap characteristics, strong carrier confinement in quantum wells, and high crystal quality due to decades of manufacturing optimization. Additionally, this material system demonstrates better tolerance to defects compared to other III-V materials and enables efficient radiative recombination mechanisms. The white LED's exceptional performance stems from the successful combination of efficient blue emission from the InGaN/GaN structure (a technology that earned the 2014 Nobel Prize in Physics) with optimized phosphor conversion, creating a robust and efficient light-emitting system. This structure outperforms direct emission from other semiconductor materials, such as AlGaInP used in red LEDs or high-indium-content InGaN used in green LEDs, the latter of which notably suffers from the "green gap" phenomenon where increased indium content leads to reduced material quality and efficiency. The comprehensive analysis of all characteristics confirms that the white LED's superior figure of merit is a direct result of its advanced material system and optimized structure, making it the most efficient and reliable option among the tested devices.

## Literature vs Our Experimental Results:

Comparing my experimental LED results with recently reported perovskite LED performances in the literature shows significant advancements in LED technology. In the work reported by Q. Wan et al. [1], perovskite nanocrystal-based LEDs achieved remarkable external quantum efficiency (EQE) of 26.7% through innovative device engineering, particularly by implementing ultrathin active layers of approximately 10 nm and utilizing $CsPbBr_3$ perovskite nanocrystals with NiO surface modification. Additionally, research on metal halide perovskite LEDs has demonstrated substantial progress, with EQE improvements from 0.1% to 11.7% over just three years, showcasing the rapid advancement in this field [2]. These results significantly outperform my experimental LEDs, where the highest EQE achieved was approximately 0.31% for the white LED.

The superior performance of perovskite LEDs can be attributed to several advanced engineering approaches: the implementation of ultra-thin active layers enabling better charge transport, precise control over the recombination zone, and enhanced light extraction efficiency. These devices also benefit from near-unity photoluminescence quantum yield and excellent color purity with tunable emission across the visible spectrum. In contrast, my conventional LED measurements showed relatively limited efficiency, with notable efficiency droop at higher power levels and lower overall performance metrics across all colors tested.

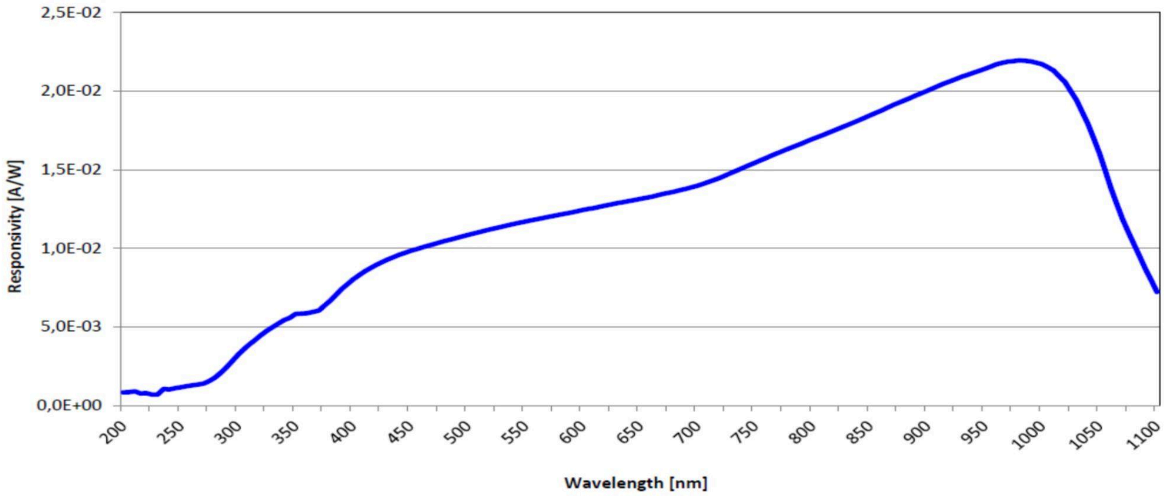
This comparison underscores the remarkable progress in perovskite LED technology and its potential for next-generation display and lighting applications. However, it's worth noting that despite these impressive efficiency values, perovskite LEDs still face challenges regarding long-term stability and commercial viability, as highlighted in the literature. These findings suggest that while conventional LED technology continues to serve current applications, perovskite-based devices represent a promising future direction for achieving higher efficiency and better color performance in LED technology.

References:
[1] Q. Wan et al., "Ultrathin Light-Emitting Diodes with External Efficiency over 26% Based on Resurfaced Perovskite Nanocrystals," ACS Energy Letters, vol. 8, no. 2, pp. 927–934, Jan. 2023.
[2] Q. Shan *et al.*, "High Performance Metal Halide Perovskite Light-Emitting Diode: From Material Design to Device Optimization," *Small*, vol. 13, no. 45, p. 1701770, Sep. 2017, doi: https://doi.org/10.1002/smll.201701770.

## Appropriate Wavelength Setting in Powermeter:

The accurate measurement of LED optical power requires careful consideration of the photodetector's wavelength-dependent response characteristics. The photodetector used in power meters, such as the Thorlabs S120VC, does not exhibit uniform sensitivity across all wavelengths. Instead, it shows varying responsivity at different wavelengths, as indicated in its specification sheet. Therefore, to obtain precise optical power measurements, it is essential to apply appropriate correction factors that account for this wavelength-dependent responsivity. These correction factors must be calculated based on the specific wavelength of the LED being measured and the corresponding responsivity value from the detector's calibration curve. This compensation ensures that the measured intensity values are accurately adjusted to reflect the true optical power output of the LED, regardless of the detector's varying sensitivity at different wavelengths.
Typical Response graph is as follows:

## Typical Response Graph




# Conclusion:

In conclusion, this experimental investigation provided comprehensive characterization of different colored LEDs through detailed analysis of their I-V, L-I, L-V characteristics, along with measurements of external quantum efficiency (EQE), power conversion efficiency (PCE), and luminous efficacy (LE). The results demonstrated that the white LED exhibited superior overall performance with the highest EQE of 0.31% and consistent efficiency across its operating range, attributed to its mature InGaN/GaN technology and phosphor conversion mechanism. The investigation also revealed the persistent challenge of the "green gap" phenomenon, evidenced by the notably lower performance of the green LED across all metrics. While these results provided valuable insights into LED behavior and performance characteristics, the relatively low efficiency values compared to state-of-the-art perovskite LEDs (reporting EQEs up to 26.7%) highlight significant opportunities for improvement in conventional LED technology. The experimental methods and analysis techniques employed in this study, including the necessary wavelength-dependent corrections for power measurements, established a robust framework for future LED characterization work. These findings contribute to our understanding of LED performance parameters and their relationships to underlying semiconductor materials and device structures, while also identifying areas for potential optimization in future LED development.