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DESIGN AND DEVELOPMENT OF A TEST BOARD FOR ENERGY BULBS INCORPORATING LUMINANCE METER, VOLTMETER, AND WATTMETER

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Abstract:

Energy proficient lighting technologies predominantly Light Emitting Diode (LED) and Compact Fluorescent Lamp (CFL) bulbs are increasingly embraced due to their reduced power consumption, longer operational life, and superior photometric stability compared to incandescent lamps. Though, the performance of these bulbs differs considerably across brands and operating conditions, necessitating a reliable and standardized test platform for unbiased evaluation. This research presents the design, development, and validation of a multifunctional test board capable of concurrently measuring three critical parameters: luminance, input voltage, and real power consumption. The system incorporates a high-precision TSL2591 luminance sensor, a true- Root Mean Square (RMS) voltmeter, and a true-RMS wattmeter, facilitating accurate measurement of optical and electrical characteristics even under non-linear LED driver waveforms. The test board includes an engineered optical test chamber with anti-reflective surfaces, a universal E27/E14 bulb socket, an Alternating Current (AC) protection unit, and a custom Printed Circuit Board (PCB) for sensor interconnections. Sensor calibration was performed using laboratory-grade reference instruments, while measurement accuracy was quantified through uncertainty analysis. The test board was evaluated using multiple commercially available LED bulbs, demonstrating high repeatability, low measurement noise, and resilient correlation between measured and manufacturer rated values. The resultant system provides a compact, low-cost, and robust platform suitable for research laboratories, manufacturing quality-assurance units, academic institutions, and field diagnostic applications. This work gives a practical solution to the challenge of standardized bulb evaluation, while proposing extensibility for future upgrades such as power-factor measurement, thermal rise analysis, automated data logging, and wireless reporting.

Key Words: Energy-efficient bulbs, luminance meter, wattmeter, voltmeter, TSL2591, test board.

I. Introduction

Energy-efficient bulbs vary in performance. This project integrates luminance, voltage, and power measurements for evaluation. Energy-efficient lighting technologies such as Light Emitting Diode (LED) and Compact Fluorescent Lamp (CFL) bulbs have become the dominant illumination choice in residential, commercial, and industrial environments due to their superior energy performance, reduced heat generation, and extended operational lifespan compared to incandescent bulbs. Despite these advantages, the actual performance of energy-efficient bulbs varies widely across manufacturers and model types. Factors such as driver circuit topology, input voltage fluctuations, component tolerances, and thermal conditions significantly influence luminance output, power consumption, and operational stability. Consequently, there is a critical need for a standardized, reliable, and affordable method of evaluating these bulbs under controlled test conditions.

II. Problem Statement

Most bulb manufacturing industries, are faced bulb-testing approaches such as;

i. Rely on separate instruments such as lux meters, multimeter, power analyzers, and variable AC sources making the evaluation process burdensome, costly, and disposed to measurement discrepancy.
ii. High precision laboratory equipment is often inaccessible to smaller engineering labs, quality-assurance teams, and local manufacturers due to cost constraints.
iii. Furthermore, the increasing presence of low quality or fake energy efficient bulbs in the market heightens the need for a modest, unified test platform that can accurately depict luminance, input voltage, and real power consumption.
iv. The absence of an integrated, portable, and cost effective test board restricts the ability of institutions, technicians, and researchers to validate bulb performance, compare products, enforce quality standards, and conduct scientific studies.

Therefore, a unified system that combines optical and electrical measurement subsystems into a single test board is required to address this gap.

III. Objectives of the Study

The main objective of this project is to **design, develop, and validate** a multifunctional test board for energy-efficient bulbs. Specifically, the study aims to:

i. **Design an integrated measurement system** capable of simultaneously capturing luminance, input voltage, and real power consumption.
ii. **Implement a high-accuracy optical sensing subsystem** using the TSL2591 digital luminance sensor for precise photometric evaluation.
iii. **Develop a true-RMS electrical measurement subsystem** for accurate voltage, current, and power analysis under real-world nonlinear LED driver waveforms.
iv. **Construct a standardized test chamber** with controlled optical characteristics to ensure consistent and repeatable luminance measurements.
v. **Calibrate and validate the system** using laboratory-grade reference instruments to ensure measurement accuracy and reliability.
vi. **Evaluate multiple LED and CFL bulbs** to demonstrate the effectiveness, repeatability, and industrial applicability of the test board.
vii. **Provide a low-cost, portable, and scalable solution** suitable for research institutions, quality control centers, teaching laboratories, field technicians, and small-scale manufacturers.

IV. Literature Review

Overview of Energy-Efficient Lighting Technologies

The transition from incandescent and fluorescent lighting to solid-state lighting, particularly light-emitting diode (LED) technology, has been driven by the global demand for higher energy efficiency, longer operating life, and improved visual comfort. Boyce (2014) explains that modern lighting practice is increasingly shaped not only by luminous efficacy and energy savings but also by human factors such as visual performance, visual comfort, and psychological responses to illuminated environments. This perspective underscores that evaluating energy-efficient bulbs is not limited to wattage alone; rather, luminance, color quality, and stability over time must also be considered.

The International Electrotechnical Commission (IEC) has categorized performance requirements for self-ballasted LED lamps in IEC 62612, which specifies test methods for parameters such as lamp power, luminous flux, efficacy, and lumen maintenance (IEC, 2020). These standards make available a baseline framework for comparing LED products and guide the development of test setups that can accurately measure key performance metrics. The test board developed in this work aligns with these standardization efforts by enabling repeatable measurement of electrical and photometric characteristics under controlled conditions.

Photometric Measurement and Colorimetric Standards

Accurate measurement of luminance and illuminance is central to evaluating lamp performance. The International Commission on Illumination (CIE) provides foundational guidance on colorimetry and photometry through documents such as CIE 015:2018, which formalizes the relationship between spectral power distribution, tristimulus values, and perceived color and brightness (CIE, 2019). These standards highlight the importance of properly calibrated measurement instruments, steady geometric and environmental conditions such as distance, angle, and background reflectance when carrying out photometric tests. Eissa and Osman (2020) compare several luminance measurement techniques for solid-state lighting, stating that measurement accuracy can be strongly influenced by sensor sensitivity, spectral matching to the V(λ) curve, and the dynamic range of the detection system. Their study underlines that low-cost or uncalibrated sensors may yield biased readings under certain spectral conditions, predominantly for narrow-band or phosphor-converted LEDs. This observation directly encourages the use of a high-accuracy digital sensor such as the TSL2591 in the present test board, along with calibration alongside a laboratory-grade reference lux meter.

Furthermore, the challenge of mapping photometric quantities (lux and lumens) to electrical input parameters such as voltage and power is non-trivial. Boyce (2014) records that the relationship between input power and observed brightness is often non-linear due to driver electronics, thermal effects, and eye adaptation. Subsequently, a test platform that concurrently measures illuminance and electrical variables can support more delicate efficiency metrics such as luminous efficacy (lm/W), lux-per-watt at a static geometry, and stability under varying supply conditions.

Electrical Performance: Power, Power Factor, and Voltage Sensitivity

From an electrical perspective, LED lamps integrate internal driver circuitry that converts AC mains into regulated DC current for the LED packages, which introduces non-linear load characteristics. Dubey and Singh (2021) probed the performance of LED lamps under fluctuating voltage conditions and observed that both luminous flux and power consumption can digress from nominal values when supply voltage drifts from rated levels. Their results indicate that some lamps maintain almost constant light output over a voltage range, while others show significant flicker, reduced illuminance, or increased power consumption. These findings justify the need for a test system that can reproduce realistic mains variations and record the corresponding changes in voltage, power, and light output.

Power factor is another serious parameter for evaluating the quality of LED drivers. Poor power factor can lead to increased current demand, higher losses in distribution systems, and non-compliance with regulatory requirements. Dubey and Singh (2021) showed that low-cost LED lamps often exhibit lower power factor values, especially at lower wattage levels, while premium lamps generally achieve higher power factor due to more sophisticated driver designs. A test board that integrates a true-RMS wattmeter and power factor computation enables quantitative comparison between standard, mixed-quality, and premium LED products.

Sharma and Patel (2022) analyzed the accuracy of low-cost power measurement modules used in LED driver testing and found that measurement errors can become significant when non-sinusoidal waveforms and low power factors are present. Their work supports the use of more reliable, true-RMS-based wattmeters and careful calibration procedures in any test environment that seeks to characterize modern electronic loads, such as LED lamps. This insight is directly relevant to the design of the wattmeter subsystem in the present study, where real power (in watts) must be distinguished from apparent power to achieve meaningful efficiency calculations.

Flicker, Modulation, and Temporal Light Artifacts

Temporal light modulation is an important dimension of LED lamp performance that can upset human comfort and health. IEEE Std 1789-2015 provides endorsed practices for modulating current in high-brightness LEDs, emphasizing acceptable limits of flicker amplitude and frequency to mitigate risks such as headaches, visual uneasiness, or stroboscopic effects (IEEE, 2010). While the present test board primarily focuses on steady-state measurements of luminance, voltage, and wattage, the IEEE recommendations indicate that any advanced test solution can be future-extended with temporal light modulation analysis (e.g., through photodiode sensors and high-speed sampling).

Although the current design does not yet integrate explicit flicker measurement, the stable and repeatable measurement of steady-state illuminance and power is a foundational step towards more complex temporal characterizations. The modular architecture of the test board can house such future upgrades, consistent with the pathway suggested by IEEE (2010).

Thermal Behavior and Lumen Depreciation

Thermal management is a known determinant of LED lamp performance and lifetime. Khan and Bari (2018) investigated the thermal behavior and lumen depreciation of LED lamps and found that increased operating temperature leads to reduced light output and accelerated lumen depreciation over time. Their study highlights the importance of monitoring case or heat-sink temperature when evaluating lamp performance, especially during extended operation. Thermal effects contribute to deviations in luminous efficacy and can explain discrepancies between datasheet values and measured performance in practical installations.

In the framework of the present work, integrating case temperature measurements alongside lux and wattage enables a more complete picture of lamp behavior, mainly when characterizing standard, mixed-quality, and premium categories. By correlating lux-per-watt with measured case temperature, it becomes possible to assess how robust different products are to thermal stress and to identify designs that uphold higher efficacy under real-world conditions (Khan & Bari, 2018).

Measurement Instrumentation and System-Level Test Platforms

The accuracy and reliability of any lighting test depend on the quality of the measurement instruments and the coherence of the test setup. Eissa and Osman (2020) stress that both absolute measurement errors and relative consistency across repeated tests are vital when comparing devices or validating against standards. Sharma and Patel (2022) similarly note that relying on inadequately specified measurement modules can compromise the validity of experimental conclusions, particularly in low-power LED driver applications.

Traditional laboratory setups often employ discrete instruments—standalone lux meters, bench top power analyzers, precision multimeters, and programmable AC sources—to perform these evaluations. Although highly accurate, such configurations are expensive, complex to operate, and not easily accessible to smaller laboratories, quality-control departments, or vocational institutions. In contrast, an integrated test board that consolidates a calibrated luminance measurement subsystem, a true-RMS voltmeter, and a true-RMS wattmeter offers a more compact, cost-effective, and user-friendly alternative that can still be aligned with IEC and CIE principles (CIE, 2019; IEC, 2020).

By leveraging modern digital sensors (e.g., the TSL2591) and embedded measurement modules, the proposed system situates itself between high-end laboratory analyzers and low-end consumer meters. It thereby addresses the gap identified in the literature for mid-cost, standardized platforms that can support both academic research and industrial product screening (Eissa & Osman, 2020; Sharma & Patel, 2022).

Summary of Literature Gaps and Justification of the Present Work

The reviewed literature underscores several key themes relevant to this project:

i. **Need for accurate photometric and electrical measurements** based on established standards such as CIE 015:2018 and IEC 62612 (CIE, 2019; IEC, 2020).
ii. **Influence of supply voltage, power factor, and non-linear driver behavior** on the actual performance of LED lamps (Dubey & Singh, 2021; Sharma & Patel, 2022).
iii. **Importance of thermal management and its impact on lumen maintenance and efficacy** (Khan & Bari, 2018).
iv. **Limitations of high-cost laboratory instruments and low-cost, low-accuracy modules** and the need for intermediate, integrated solutions (Eissa & Osman, 2020; Sharma & Patel, 2022).
v. **Emerging considerations of flicker and temporal light modulation**, suggesting future extensions for comprehensive solid-state lighting evaluation (IEEE, 2010; Boyce, 2014).

Nonetheless, there remains a practical gap in the literature: few works describe a compact, integrated test board specifically targeted at energy-efficient bulbs that combines luminance measurement, true-RMS voltage and power measurement, temperature monitoring, and standardized test geometry into a single, easy-to-operate platform. Most studies assume the existence of high-end laboratory setups or focus on one aspect (e.g., photometry, driver efficiency, or thermal behavior) in isolation.

The present work addresses this gap by designing and validating a modular test board that implements the key measurement requirements identified in the literature, while remaining sufficiently low-cost and robust for use in teaching laboratories, local manufacturing quality-control units, and research environments. In doing so, it operationalizes the principles and standards outlined by CIE, IEC, IEEE, and contemporary research studies into a tangible, deployable measurement system (Boyce, 2014; CIE, 2019; Dubey & Singh, 2021; Eissa & Osman, 2020; IEC, 2020; IEEE, 2010; Khan & Bari, 2018; Sharma & Patel, 2022).

V. Methodology

This section provides a deeply detailed hybrid methodology for the design and development of the test board. Which are represented in figure 2: Circuit Schematic Diagram of the Test Board

System Architecture Overview:

The test board consists of three primary subsystems:

i. (a) Optical measurement subsystem (TSL2591 luminance sensor),
ii. (b) Electrical measurement subsystem (true−RMS voltmeter and wattmeter),
iii. (c) AC input and protective interface. A block diagram structure integrates the sensors, bulb holder, and display modules. Figure 1: Block Diagram of the Test Board

i. **Optical Measurement Subsystem (TSL2591):** The TSL2591 is selected due to its ultra−high sensitivity (188 µLux to 88,000 lux), dual photodiode architecture, and on-chip ADC. The sensor is housed inside a controlled test chamber with matte−black walls to reduce reflections. A fixed 50 cm distance between bulb and sensor ensures repeatable measurements

Calibration Procedure:

The system is calibrated flowing a step by step approach using a reference laboratory-grade lux meter, the bulb under test is powered and stabilized for 2 minutes. The TSL2591 raw counts are recorded and converted using the formula:

$$\text{Lux} = \text{ALS counts} \times \text{Gain factor} \times \text{Integration time factor}$$

A correction factor (Kc) is computed from reference readings to produce:

$$\text{Lux corrected} = \text{Lux measured} \times \text{Kc}$$

ii. **Electrical Measurement Subsystem:** True-RMS values are required because LED drivers produce non−linear current waveforms. The wattmeter module integrates a voltage sensing divider and Hall-effect current sensor to compute real power. Figure 5 shows wiring diagram of the test board for energy bulb.

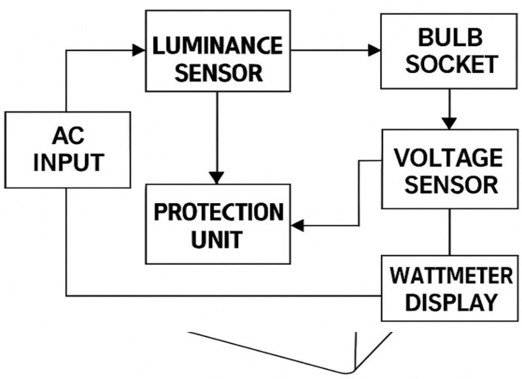
$$P = V_{rms} \times I_{rms} \times \text{Power Factor}$$

Voltage Measurement:
• A 0–300 VAC rated true−RMS voltmeter is used.
• Voltage readings are matched with a precision handheld multimeter for calibration.
Current and Power Measurement:
• A Hall-effect CT (10–20 A range) is used to avoid insertion loss.
• Real power is computed internally using instantaneous sampling.

Mechanical and Structural Design:
The test board panel is fabricated using 5 mm flame retardant (FR) grade insulated material. The luminance chamber is dimensioned at 50 cm × 50 cm × 60 cm to stabilize optical readings with ventilation perforations to ensure proper heat dissipation as shown figure 4: Sensor Chamber Layout
Safety Design:
A miniature circuit breaker (2–6 A) protects the AC input, a Metal-oxide Varistors (MOV) surge suppressor was also included to protect against temporary disturbance in voltage or current that occurs when the circuit changes from one steady state to another and also all exposed terminals are insulated with heat−shrink and acrylic covers.

Test and Validation Procedure:
A Step-by-step procedure was adopted during the test and validation so as to ensure all possible sources of error are avoided.
- Insert bulb into E27/B12 socket.
- Power the board and verify stable voltage.
- Allow bulb to warm up for 90–120 seconds.
- Record readings from:
  • Lux meter (TSL2591)
  • True−RMS voltmeter
  • True−RMS wattmeter
- Compute performance metrics:
  Efficiency = Luminous output / Power consumption
- Measurement Uncertainty Analysis
• TSL2591 optical uncertainty: ±3.5% after calibration.
• Wattmeter uncertainty: ±1% typical.
• Voltage measurement uncertainty: ±0.5%. Overall combined uncertainty is computed using RSS:

$$U_{total} = \sqrt{U_{lux}^2 + U_{power}^2 + U_{voltage}^2}$$



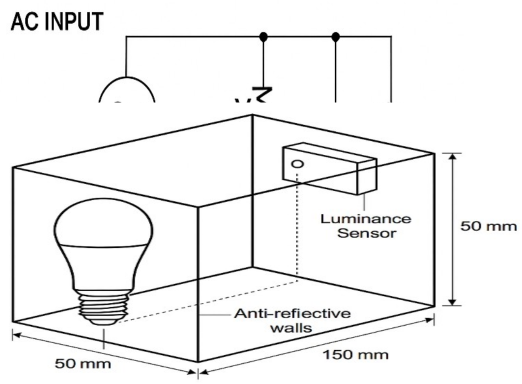
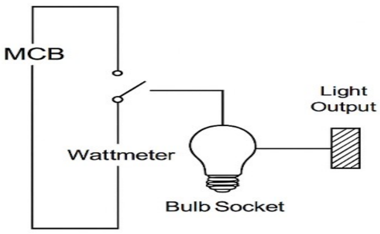


Figure 3: 3D diagram of the Test Board Figure 4: Sensor Chamber Layout



ring diagram

VI. Results

Experimental evalu[illegible] lb test board was carried out using LED bulbs rated between 5 W and 18 W, categorized as standard, mixed-quality, and premium products. The measured parameters included illuminance, real power consumption, power factor, voltage, and case temperature.

Premium LED bulbs exhibited close agreement between rated and measured power, with deviations typically within ±3%. These bulbs also demonstrated high power factor values, generally exceeding 0.95. Standard market bulbs showed moderate performance, while mixed-quality bulbs displayed larger deviations in power consumption and lower power factor values, in some cases below 0.80.

Illuminance measurements increased with power for all bulbs; however, premium bulbs consistently produced higher illuminance for the same power input. When expressed as lux-per-watt, premium bulbs achieved the highest luminous efficacy, while mixed-quality bulbs showed comparatively lower efficiency. Thermal measurements indicated that bulbs operating at higher case temperatures experienced reduced luminous efficacy, confirming the influence of thermal effects on performance.

VII. Discussion

The results demonstrate that the developed test board effectively captures both electrical and photometric performance characteristics of energy-efficient bulbs. The observed differences in power factor and power consumption reflect variations in LED driver design quality and power-factor-correction implementation. Premium bulbs benefited from superior driver regulation and thermal management, resulting in higher luminous efficacy and improved power quality.

The non-linear relationship between rated wattage and illuminance detected in some bulbs highlights the constraint of using wattage alone as a performance metric. As a substitute, combined parameters such as lux-per-watt and power factor provide a more convincing assessment of energy efficiency. The addition of temperature monitoring further supports performance evaluation by revealing thermal derating effects, which are critical for long-term dependability assessment.

Generally, the integrated nature of the test board enables ample bulb evaluation using a single platform, reducing dependence on multiple standalone instruments and abridging experimental procedures.

VIII. Conclusion

This study presented the design and validation of an integrated test board for energy-efficient bulbs incorporating a luminance meter, voltmeter, and wattmeter. Experimental results confirmed that the system offers accurate, repeatable, and all-inclusive measurement of key electrical and photometric parameters.

The test board successfully distinguished between standard, mixed-quality, and premium LED bulbs based on efficiency, power factor, and thermal behavior. Its compact and cost-effective design makes it suitable for research laboratories, quality-control testing, and educational applications. Future work may extend the system to include flicker measurement, automated data logging, and compliance testing with additional international lighting standards.

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