



## Research Paper

# A hybrid prediction method on luminous flux maintenance of high-power LED lamps



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## HIGHLIGHTS

- Thermal modeling and temperature measuring are applied to predict the  $T_j$  of LED lamps.
- The lumen maintenance of LED lamps is further estimated with the predicted  $T_j$ .
- The thermal resistance model of LED lamps is simplified into a one-dimensional model.
- The estimation method is efficient to predict the luminous maintenance of LED lamps.
- The proposed method is expected to be useful for the fast qualification of LED lamps.

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## ABSTRACT

A hybrid method, applied thermal modeling and temperature measurement, is proposed to estimate the junction temperature ( $T_j$ ) of high-power light-emitting diodes (LEDs) at system level, and further project long term lumen maintenance of LED lamps. First, 3D finite element modeling on commercial LED lamps is performed based on lamp structure and material information to find a steady and reliable relationship between the junction point and a referenced point on the heat sink. Then, accurate thermal measurement is conducted on the heat sink to calibrate and verify the finite element model. The predicted  $T_j$  of LEDs from modeling, in conjunction with LM-80 luminous maintenance data using TM-21, is applied to project the luminous flux depreciation at the system level. The proposed approach is validated by aging tests at room ambience. Results show the thermal resistance modeling can be simplified into a one-dimensional model when a LED lamp operates in a steady situation. Thus, the  $T_j$  of LED lamps operating at any specified ambient temperature can be achieved quickly. The estimation method for predicting luminous maintenance of LED lamps is efficient and fast. The proposed method is expected to be useful for the fast qualification of LED lamps.

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## 1. Introduction

Light-emitting diodes (LEDs) have attracted growing attention for their advantages over traditional light sources, such as high luminous efficiency, energy saving, and long lifetime [1]. However, more than 70% of the input electrical energy is converted into heat in general commercial products [2]. With continuously increasing power density, heat generation in the active layers of LEDs has overheated p–n junctions. The temperature of the p–n junction, named as junction temperature ( $T_j$ ), is regarded as one of crucial parameters for LED reliability. LED products suffer many problems because

of high  $T_j$ , like quantum efficiency reduction, spectral shift, and color shift or even the early decommissioning of LEDs [3]. The reliability of LED products has recently become a big concern.

The lifetime of a LED lamp is defined by the Illuminating Engineering Society (IES) under their standards, LM-79 and LM-80. Likewise, the Energy Star TM-21 procedure specifies the process for lumen maintenance over time with its current input and working condition [4]. These procedures are time-consuming; for example, LM-80 requires at least 6000 hours of testing achieving reliable long term predictions. Reports state that IES LM-84 and TM-28 require a minimum of 3000 hours of testing [5], and such a test duration seems still too long for the rapid development of LED products. In recent years, a few studies have been carried out on LED lamp reliability. Ignacio et al. [6] presented a reliability testing method for LEDs based on the overstress life test method. However, when they

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tried to evaluate the reliability of portable lamps, very few lamps passed the test [6]. Considering the degradation of the epoxy lens and plastic package, Koh et al. [7] introduced simplified Eyring models to predict the life of a lighting system under changing conditions. Moreover, researchers have developed some reliability models for extrapolating the lifetime of LED lamp system, such as a generic system level approach [8], an approach using design for reliability [9], a hierarchical life-prediction model [10], and a non-linear filter-based approach [11]. However, most of those methods ignore the existing reliability data from the qualification process of the LED package or module, and the long-term luminous depreciation testing or/and the complex reliability modeling cannot be avoided to implement those methods. Evidently, a fast lifetime prediction of LED lamps or luminaires remains a challenging task.

Modeling and simulation are important activities, because they can help provide an accurate prediction of final device performance and reliability [12]. Li et al. [13] launched the research to LED integrated light source thermal issues on the principle of heat transfer, and proved that LED thermal field analysis based on Multi-physics finite element simulation is accurate, feasible, and effective. Meanwhile, Ye et al. [14] developed an electrical–thermal–luminous–chromatic model to predict the light performance with thermal management under in-situ temperature while considering a series of thermal problems resulting from the drive of increased electrical currents to achieve high luminous output for phosphor-converted white LED. Aiming to enhance heat dissipation and further minimize  $T_j$ , many studies were conducted to fulfill thermal designs with the help of thermal modeling and analysis [15–17].

Focusing on the thermal modeling of the LED lamp system, Costa and Lopes [18] presented a numerical study concerning an improved heat sink for LED lamps operating under natural convection conditions. Further thermal module designs and analyses on 230 W LED lamps with different incline angles were carried out [19]. Meanwhile, Zhao et al. [20] conducted a thermal model design and analysis for high-power LED automotive headlight cooling devices, and Wang et al. [21] had a thermal design for a LED lamp with air convection. Modeling analysis on the thermal performance of a LED lamp showed that critical parts can be determined with thermal simulation tools when designing higher power LED lamps, and solutions for thermal problems can be achieved [21–23]. Impressively, employing a two-resistor compact thermal model, Yurtseven et al. [24] analyzed the temperature distribution of LED luminaires, and believed that use of the two-resistor model and measurement combination is a fast and easy way of predicting thermal behavior of the LED system with acceptable errors. Muller et al. [25] had further tried to address several issues regarding the determination of the junction-to-case thermal resistance for LED packages. Especially, the so called “point of separation” of the underlying dual-interface method was investigated; and experiments and simulations, investigating the environmental influences on this crucial point, revealed that the point of separation changes depending on the thermal boundary condition in the case of the LED module [25]. Evidently, thermal modeling can be employed to analyze LED  $T_j$ , while an effective and fast method to obtain the  $T_j$  of LED lamp systems has still not been achieved.

Generally, LED  $T_j$  measurement methods can be divided into thermal, optical, and electrical measuring methods as per a concrete measured parameter, such as measuring directly with an embedded microsensor along LED chip [26], determining through a stable linear relationship between  $T_j$  and LED light power [27,28], and a certain  $T_j$  relationship to peak wavelength or blue–white ratio of LED devices with self-excited photoluminescence signal [29], or to reverse current in InGaN LEDs [30]. Among the  $T_j$  measurement methods, the pulsed  $T_j$  measurement (PJTm) is the most appealing method [31–33]. The PJTm method is based on an evident linear relationship between LED  $T_j$  and its associated voltage in a certain range

of temperature and the forward current. Uncertainty studies or error comparisons on  $T_j$  measurement have recently become a popular topic of discussion [34,35]. Ye et al. [36] proposed an improved pulse-free direct  $T_j$  measurement method for HV LEDs to reduce errors and to achieve in situ  $T_j$  measurements with DC currents, simpler setups, and a fewer step sequence. However, generally, LED packages or LED modules are assembled with a heat sink and an optical structure. Implementing the above  $T_j$  measurement approaches for LED lamps system with complex geometry structure is impractical [37], unless the system is disassembled.

Over the last decade, although many studies were carried out for LED packages and modules, the measurement or prediction of the lifetime of LED lamps or luminaires is still a big challenge. According to our previous investigation [37], the significant temperature gap of 5 °C–12 °C was found at the heat sink surface of five types of LED lamps with/without lampshade. This indicates that the operating ambient condition of the LED package or module assembled in a lamp, compared with that of the LED package or module alone, is more abominable, and indeed the junction temperature of the LED package or module assembled in a lamp is at a higher stress level. Therefore, the thermal performance of a LED package or module is different from a LED package or module assembled in a lamp. It should be highlighted that the long lifetime of a LED light source (or package and module) cannot translate into the long lifetime of a product if the thermal design of a LED product is not done properly, and the luminous maintenance test of product level is impractical. Developing a fast methodology to accurately predict the lifetime at product level is urgently needed.

In this work, a hybrid method that combines thermal modeling and temperature measurement is proposed to estimate the  $T_j$  of LEDs at the system level, and further to project long term lumen maintenance of LED lamps. Such a method will avoid the time-consuming luminous depreciation test or/and the complex reliability modeling at product level as well as overcome the measurement of soldering temperature that requires the disassembling of the system. The hybrid method is an effective and fast method for predicting the lifetime of LED lamps at product level with the existing reliability data of the LED package or module. The main ideas of the proposed method are as follows. 3D finite element modeling is performed based on the luminaire structure and material information. Then, accurate thermal measurement is conducted on the heat sink temperature to calibrate and verify the finite element model. Predicted  $T_j$  of LEDs from modeling, in conjunction with LM-80 luminous maintenance data, is used to project the luminous flux depreciation and lifetime at the system level. To demonstrate how it works, three types of commercial LED lamps are selected in this investigation. Thermal modeling is performed to predict the overall temperature distribution, to find a steady and reliable relationship between the junction point and a referenced point on the heat sink (RBJR). To validate the predicted junction temperature, the thermal measuring experiments using thermal transient tester (T3ster) are applied. The predicted  $T_j$  is suggested to apply on the lifetime estimation of a LED lamp based on the relationship between the lifetime of the LED package and the junction temperature. Moreover, aging test results for one lamp operating at room ambience is utilized to validate the estimated lifetime.

## 2. Methodology

### 2.1. System thermal modeling

Thermal resistance in a real lamp is extremely complex, as illustrated in Fig. 1, normally distributed in LEDs through packaging materials, solder joint, substrate thermal conductor, and heat sink.

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