Optimum design domain of LED-based solid state lighting considering cost, energy consumption and reliability

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Abstract

Design parameters of LED-based solid state lighting products are interdependent and the corresponding requirements are dictated by operating conditions. We propose a scheme to define optimum design domains of LED-based luminaires for a given light output requirement by taking cost, energy consumption and reliability into consideration. First three required data sets to define design domains are expressed as contour maps in terms of the forward current and the junction temperature (I F and Tj): (1) face lumen and cost requirement as lumen/LED; (2) power consumption and energy requirement as luminaire efficacy (LE); and (3) reliability requirement as L70 lifetime. Then, the available domain of design solutions is defined as a common area that satisfies all the requirements of a luminaire. The proposed scheme is implemented for a wall wash light and the optimum design solutions are presented.

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1. Introduction

Recently LED-based luminaires have emerged rapidly for commercial and residential applications. For a required light output, the optimum design of a LED-based luminaire can be achieved by considering cost, energy consumption and reliability.

Design considerations for LED-based luminaires are unique in that many design solutions are possible for the same required light output unlike the conventional light sources (e.g., compact fluorescent light, incandescent light, etc.). This is due to the well-known fact that the lumen output that each LED produces is a function of the driving current, I F, as well as the junction temperature, Tj.

Fig. 1 illustrates the details. The luminous flux of LEDs increases as the driving current increases, but the corresponding luminescent efficacy decreases at a higher driving current because the luminous flux is not linearly proportional to a driving current. More importantly, when a higher driving current is used, heat flux becomes proportionally larger, resulting in a higher junction temperature. This increased junction temperature not only decreases the luminous flux but also significantly affects the rate of lumen maintenance (i.e., life time). A lower driving current can be utilized if more LEDs are used in the light engine of a luminaire. Yet this is often not the most desired solution due to the high cost of LEDs.

In an LED-based luminaire design, all design parameters are interdependent and the corresponding requirements are dictated by operating conditions (I F and Tj). This paper suggests a methodology to define the optimum design domains of LED-based luminaires considering cost, energy consumption and reliability. The required data sets to define design domains are described in Section 3. An application using the requirements of wall wash light is provided in Section 3.

2. Design considerations and required data sets

Optimum design of LED-based luminaires can be achieved by considering cost, energy consumption and reliability. These design parameters can be expressed as lumen/LED, luminaire efficacy, and L70 lifetime, respectively. Since they are a function of operating conditions, the parameters can be quantified in the domain of junction temperature (Tj) and forward current (I F).

This section describes the three interdependent design parameters and defines the data sets required to obtain them. Test data obtained from a commercial phosphor converted LED are used to illustrate the concept.

2.1. Cost (lumen/LED)

The Department of Energy (DoE) of U.S. published the requirements for solid state lighting luminaires [1]. To deliver a required light output, two different approaches can be considered depending upon the nature of applications. For medical and military applications where stringent reliability requirements must be met, the required light output should be delivered at a junction temperature that is sufficiently low to satisfy the high reliability standards. For a given passively or actively-cooled luminaire, a low junction
Temperature can be achieved only by a low forward current level, which forces to employ as many LEDs as needed. For commercial and residential applications, however, LED-based luminaires should use only a minimum number of LEDs to be cost-effective and thus to be competitive with the conventional light sources. Therefore, the light output of a single LED at a specified condition is a very important parameter. Since the light output is a function of forward current and junction temperature, the light output has to be measured at various forward current and junction temperature conditions.

Fig. 2 shows an experimental setup used to acquire light output at different currents and junction temperatures. An LED (CREE XR-E) is mounted on a thermoelectric cooler (TEC) in an integrating sphere. The LED has a conformally coated phosphor layer on the chip and encapsulated with transparent silicone. The top part dome is glass. The package is surrounded with the aluminum reflector. The TEC controls the solder point temperature of LED (Ts) and the integrating sphere (SMS-500: Labsphere) equipped with a spectroradiometer system measures the spectral power distribution (SPD) of the LED at the various operating conditions. The sampling interval of the spectroradiometer is 1 nm. The measurement range of wavelength is 360–1000 nm. The TEC is controlled by a thermal controller (LB 320: Silicone Thermal, Co. Ltd.) using an input provided by a T-type thermocouple directly mounted on the solder point surface. The setup can adjust the solder point temperature from −40 to 125 °C with a resolution of 0.1 °C.

The junction temperature can be estimated by the well-known forward voltage method [2]. The method is valid only when a pulsed current with a very short duration is used so that the junction temperature does not change during forward voltage measurement. For the SPD measurement, however, the spectroradiometer requires an integration time [3], which is usually much longer than the short pulse duration for the forward voltage method: a typical integration time for a full white light spectrum is 100–1000 ms. As a result, an additional increase of junction temperature is unavoidable during the SPD measurement. In order to avoid this undesired error in junction temperature measurement, an LED is subjected to a steady-state condition inside an integrating sphere for accurate junction temperature measurement. With the 4π configuration in Fig. 2, a current is applied to the LED continuously until the solder point temperature reaches a preset value which is maintained by controlling the TEC. Once the solder point temperature is stabilized, the SPD and the forward voltage of the LED are measured simultaneously.

The SPDs have been measured at various solder point temperatures and forward currents: Ts from 65 to 125 °C with a constant interval of 15 °C and If from 300 to 1000 mA with a constant interval of 100 mA. The total number of measurements is 40. Typical SPDs obtained at Ts = 65 and 125 °C at If = 300 and 1000 mA are shown in Fig. 3. The radiant flux and the corresponding luminous flux obtained from all 40 measurements are shown in Fig. 4a and b, respectively. As expected, the luminous flux increases as the solder point temperature decreases under a constant current.

The measurement data obtained for solder point temperatures can be converted to the junction temperature domain through the relationship between junction temperature and solder point temperature, which can be expressed as [4–6]:

\[
T_j = T_s + P(1 - \eta_p)R_{th} = T_s + I_fV_f(1 - \eta_p)R_{th}
\]

(1)

where \(T_s\) is the solder point temperature, \(P\) is the total electrical power consumption in W (\(= I_fV_f\)), \(\eta_p\) is the LED power efficiency (the radiant flux divided by the total electrical power input), \(I_f\) is the forward current, \(V_f\) is the forward voltage and \(R_{th}\) is the thermal resistance between the chip and the solder point (8 °C/W for the LED tested in this study [7]). It is important to note that power efficiency in Eq. (1) was often ignored in the thermal analysis of low power LEDs due to low efficiency [8,9]. For high power LEDs with typical power efficiency of 15–30%, the effect of the power efficiency must be considered in a thermal analysis.

The forward voltage is measured first as a function of solder point temperatures (Fig. 5a), from which the total electrical power consumption is determined. The results are shown in Fig. 5b. The power efficiency then can be determined simply by dividing the total power consumption by the radiant flux amount shown in Fig. 4a, and the results are shown in Fig. 6. The power efficiency varies significantly with the forward current.

The solder point temperatures in Fig. 6 can be converted to the corresponding junction temperatures using Eq. (1). The converted power efficiency as a function of junction temperature is shown in Fig. 7. It is worth noting that the power efficiency decreases almost linearly as the junction temperature increases and the rate of the power efficiency reduction remains the same regardless of the current.

The luminous flux data of Fig. 4b can be also presented in the junction temperature domain using Eq. (1) and the power efficiency data. The converted luminous flux data is shown in Fig. 8. From the data in Fig. 8, a contour plot of the luminous flux of a single LED in a domain of the forward current and the junction temperature can be determined (Fig. 9). The contour plot shows the distinctive characteristic of LED luminous flux, which depends on the junction temperature as well as the forward current.

2.2. Energy consumption (luminaire efficacy)

One of the key attributes of LED lighting is low power consumption. In other words, LED-based luminaire can deliver the same amount of luminous flux with lower power consumption compared to the conventional light sources. This property is expressed as luminaire efficacy [10], which is defined as the total lumens produced by a luminaire divided by the total wattage drawn by the power supply/driver, expressed in lumens per watt (lm/W); i.e.,

\[
LE_{\text{luminaire}} = LE_{\text{LED}} \times F_{\text{fixture}}
\]

(2)
where $\eta_{\text{luminaire}}$ is the luminaire efficacy (lm/W), $\eta_{\text{LED}}$ is the luminous efficacy of each LED (lm/W) and $\eta_{\text{fixture}}$ is the luminaire fixture efficiency (%). It is important to note that the luminaire efficacy remains the same regardless of the number of LEDs used in a luminaire as long as the forward current and the junction temperature remain the same.

Luminaire efficacy is a function of luminous flux and power consumption. The luminous efficacy of an LED can be obtained by dividing the lumen/LED (Fig. 9) by power consumption (Fig. 5b). The luminaire efficacy contour is shown in Fig. 10, where the fixture efficiency of 90% is assumed based on the values provided in Ref. [11]. The light output does not increase linearly with the increasing current due to the efficiency drooping [12–14] at a fixed junction temperature and it is well known that LED light output decreases with an increasing junction temperature at a fixed current. As expected, the luminaire efficacy increases with the decreasing forward current and junction temperature.

2.3. Reliability ($L70$ lifetime)

All electrically powered light sources experience light reduction as they continuously illuminate light under normal operating conditions. This is known as lumen depreciation [15]. The lifetime of an LED is characterized by its $L70$ lifetime, which is the time to 70% of an initial light output. In order to estimate the LED lifetime, major LED manufacturers have adopted IESNA LM-80 [16]. The document prescribes standard test methods to measure lumen maintenance of LEDs under controlled conditions (constant junction and ambient temperatures with a constant DC mode). Since LEDs have very long expected lifetime (>30,000 h), a complete lifetime test is not practical. The LM-80 recommends a minimum of 6000 h testing with 1000 h measurement interval. Then, the lifetime of LED has to be extrapolated from the test data. Although the empirical equation of LED lumen depreciation is known to take an exponential form [5,6], LED manufacturers use their own extrapolation schemes [17,18]. The LED lifetime is dictated by operating conditions: longer lifetimes are expected at the lower junction temperature and the lower forward current. Ambient temperature is also an important factor for the LED lifetime. When LEDs are exposed to high temperature ambient conditions, the package of LEDs is degraded [19,20]. The well-known package degradation mechanisms are reflective coating degradation and optical lens yellowing. They not only decrease the total light output but also change CCT [5,20,21].

Fig. 11 shows the $L70$ lifetime at different junction temperatures and forward currents at two different ambient temperatures of 65 °C and 75 °C [18]. The data in Fig. 11 is converted to contour plots in Fig. 12. The contour plot clearly shows that the lifetime of LED is more sensitive to the junction temperature than the forward current under the same ambient temperature.

2.4. Extra consideration: minimum junction temperature

In the previous sections the data has been shown over the whole junction temperature range. In practice, the junction temp-
Temperature is always higher than the solder point temperature (and the ambient temperature), and there should be a low bound of the junction temperature, below which a design solution is not valid.

The thermal network model can be utilized to determine the low bound. Fig. 13 illustrates a simplified thermal resistance network model of the LED considering only the downward path through the heat slug to the mold, substrate and solder point [4].

Fig. 5. (a) Forward voltage and (b) electrical power consumption at different forward currents as a function of solder point temperatures.

Fig. 6. Power efficiency of LED at different currents as a function of solder point temperatures.

Fig. 7. Power efficiency of LED at different currents as a function of junction temperatures.

Fig. 8. Luminous flux at different currents as a function of junction temperatures.

Fig. 9. Lumen/LED as a function of \( I_f \) and \( T_j \).
The upward path through the encapsulant to the lens surface can be ignored since the upward heat transfer is less than 1% of the total heat transfer.

The network model can be further simplified by breaking the full network into two parts: internal (conductive) and external (convective and radiative) resistances. It is expressed as:

\[ q = \frac{T_s - T_a}{R_{cr}} - \frac{T_j - T_s}{R_{js}} \]  

(3)

where \( q \) is the heat generated by the LED (W) at a given current; \( R_{js} \) is the conduction resistance in (°C/W); \( R_{cr} \) is the effective external resistance (°C/W); \( T_j \) is the junction temperature (°C); \( T_s \) is the solder point temperature of the downward path (°C); and \( T_a \) is the ambient temperature. The effective internal thermal resistance for conduction, \( R_{js} \), and the effective external thermal resistance (including convection and radiation), \( R_{cr} \), can be defined as:

\[ R_{js} = \frac{t}{k A_{cd}} \quad \text{and} \quad R_{cr} = \frac{1}{A_{cr}(h + h_r)} \]  

(4)

where \( t \) is the thickness (m), \( k \) is the heat conductivity (W/mK), \( h \) is the convection coefficient (W/m²), \( h_r \) is the effective convection coefficient for radiation (W/m²), \( A_{cd} \) and \( A_{cr} \) are the effective areas of the conduction and the convection/radiation (m²), respectively.

Since \( T_j \) is always higher than \( T_s \), the lowest possible junction temperature \( T_{j\min} \) can be defined as:

\[ T_{j\min} = R_{js} q_{\min} + T_{s\min} \]  

(5)

where \( q_{\min} \) is the minimum heat generation at a given forward current, which can be defined as:

\[ q_{\min} = P_{\min} \left( \frac{1}{\eta_{max}} \right) \]  

(6)

The minimum power and the maximum power efficiency at a given forward current can be obtained from Figs. 5b and 6, respectively.

The power consumption and the power efficiency of LED are dictated by the LED junction temperature. The minimum power consumption for a given forward current can be achieved at the
highest junction temperature while the maximum power efficiency for a given forward current can be achieved at the lowest junction temperature (Fig. 7). Fig. 14 shows the minimum junction temperatures as a function of ambient temperatures obtained from Eqs. (5) and (6). The junction temperatures shown in Fig. 14 are the practical lower bound under the ambient temperatures.

3. Implementation for wall wash light

In order to illustrate the proposed approach, wall wash light was selected as an example for implementation. Wall wash lights (Fig. 15) are used to illuminate walls in buildings, bridges and towers for decoration and lighting purpose. The requirements of a wall wash light are specified as [1]:

- Luminous flux: 575 lm.
- Luminaire Efficacy: 40 lm/W.
- L70: 35,000 h.

Assuming the same LED (CREE XR-E) is used for the wall wash light, the lumen/LED (Fig. 9) can be used first for cost consideration. The lumen output that each LED has to deliver is:

\[
\text{Lumen output} = \frac{575}{N} \times \frac{1}{F_{\text{fixture}}} \tag{7}
\]

where \(N\) is the number of LEDs used in the luminaire and \(F_{\text{fixture}}\) is the luminaire fixture efficiency. Considering again the typical fixture efficiency of 90\%, the above relationship can be used to convert
Fig. 18. Domain of L70 lifetime for wall wash light under an ambient temperature of 75 °C.

Fig. 19 shows design solutions for a wall wash light under an ambient temperature of 75 °C. Any operating conditions within the area satisfy the requirements for the corresponding number of LEDs. Yet several points in the domain offer solutions that would carry more importance in practice. The solutions indicated by red dots in Fig. 19 offer the maximum luminaire efficacy and lifetime within each LED-quantity based solution line: i.e., the lowest current as well as junction temperature. These solutions require a more expensive cooling solution to maintain the low junction temperature. As opposed to these, the solutions indicated by blue dots offer solutions with the most relaxed thermal requirement. The luminaire maintenance is obviously compromised in these solutions.

The optimized operating condition for a given number of LEDs can be chosen along the lumenerg/LLED in lines in Fig. 19. This is illustrated for the solution with five LEDs. If the junction temperature is to be 95 °C, the proper current level should be 645 mA (marked as “■” along the five LED solution line in Fig. 19). If the current levels are higher than the value along the dashed line (marked as “○” in Fig. 19) while maintaining the same junction temperature (95 °C), the luminaire will produce the face lumen higher than the required value at the points marked as “x”. The lumenerg/LLED will be 138 and 152 lm and the total luminous flux of the luminaire will be 621 and 684 lumen, respectively. This extra luminous flux will increase the L70 lifetime. It should be noted that this condition requires a better thermal management solution to maintain the same junction temperature.

4. Conclusion

Design parameters of LED-based luminaires have been analyzed to suggest a design domain that optimizes cost, energy consumption and reliability. The required data sets were lumen/LLED, luminaire efficacy, and L70 lifetime. The data sets were obtained by measuring the SPD of an LED as a function of forward current as well as junction temperature (Iₖ and T). The minimum junction temperature limit was also defined as a low bound of a valid design domain. The proposed scheme was implemented for a wall wash light and the optimum design solutions were presented. The scheme is general and can be applied to LED-based luminaires with either passive or active cooling solutions.

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