Dimensionless Correlation between Empirical Modeling and T3ster Measurements for the Dynamic Thermal Characterization of the PWM-mode Current Driving UVLED

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Abstract
The measurement of the junction temperature of light emitting diodes (LEDs) has been crucial for the thermal management. It is more important for the applications of the ultra-violet light emitting diode (UVLED) with a low efficiency generating more heat and with the PWM-mode current driving at a higher peak current than the one with the DC-mode current driving. In this paper, the dynamic junction temperature of the UVLED with 365nm peak wavelength is characterized by the empirical modelling for the PWM-mode current driving modes with different duty cycles and periods using T3ster with the time-resolved measuring based on the JESD 51-14 and 51-51 for the DC-mode current driving. The PWM-mode response of the junction temperature rise and its fluctuation are normalized by the DC-mode response and its PWM-mode response respectively in terms of duty cycles (ranged from 10–90\%) and periods (ranged from 0.1msec. to 1sec.). The DC-mode junction temperature rise with respect to applied dc currents can be direct measured by T3ster. Based on the DC correlation, the PWM-mode correlations with the power-exponential function of the normalized peak junction temperature rise and its fluctuation is established. With the proposed correlations, the normalized mean junction temperature rise as the average of the dynamic junction temperature rise over a period is found. The normalized thermal resistances of the peak, mean, fluctuation are inferred from the correlations. Furthermore, the maximum permissible pulse current is able to be determined based on the maximum rating of the DC junction temperature and the consideration of current crowding. Finally, the pulse density modulation (PDM) mode of current driving is also discussed. Those successful empirical modeling is helpful for the thermal design and thermal management for applications of UVLED with PWM-mode driving.

1. Introduction
LEDs need to be strobed at some higher pulsed current whenever high light output for a short duration is necessary such as the case with pulsed width modulation (PWM) for dimming control in LED lighting, displays, and backlight. It is known the higher pulse current induces the more localized current crowding with overheating and leads to the thermal runaway, and eventually may result in the early catastrophic damage \([1]\). An LED junction temperature measurement technique for a RGB LED lighting system driven by PWM-mode current such that accurate control of the color mixing without expensive feedback of light sensors had been studied \([2]\). Manninen and Orreveläinen studied the influence of the PWM dimming on the LED peak wavelength and concluded that the spectral and color variations is so significant and should be taken into account when designing satisfactory light source based on AlGaInP LEDs \([3]\).

The LED dynamic junction temperature in the transient state before thermal equilibrium driven by pulse-mode current driving for LED was studied with the empirical measurement and simulation \([4]\). And \([5]\) demonstrated the empirical measurement of dynamic junction temperature both in the transient state and steady state driven by the PWM-mode current for VCSEL based on different duty cycles and frequencies with the algorithm for the transient state was proposed. Reference \([6]\) studied the thermal time constants in frequency domain with the small signal method and compared the junction temperature oscillation driven by PWM and PFM-mode currents \([7]\).

Reference \([8]\) compares the energy efficiency and the interaction with living organisms between PWM-mode and DC-mode current driving of LEDs.

The thermal performance of high power LED packages at PWM-mode current driving has been reported \([9]\). By utilizing the analogy between the thermal and electrical RC circuits, the theoretical dynamic junction temperature rise and its fluctuation was simulated by SPICE comparing to the measurement results through the peak wavelength shift method.

It can be found that the dynamic LED junction temperature, especially the peak and its fluctuation for PWM-mode cases with different periods (frequencies) and duty cycles is important for reliability and performance optimization. However, it is usually not available in the datasheet provided by manufacturers. In this paper, the correlation of normalized dynamic junction temperature rise and its fluctuation in terms of period and duty cycle for PWM-mode based on the DC-mode is proposed.

2. Thermal Characterization and Correlation

Fig. 1 UVLED and T3ster for junction temperature measurement.
The UVLED and T3ster for measurement of junction temperature rise $\Delta T_j$ of LEDs with respect to the heat sink is shown in Fig. 1.

### 2.1 The DC-Mode

In Fig. 2, the cooling curves with the junction temperature rise $\Delta T_j$ with respect to heatsink temperature at 25°C during cooling for $I_{dc}$ ranged from 50 to 200mA are obtained from T3ster. The maximum $\Delta T_j$ at onset of cooling is defined as $\Delta T_{j,dc}$. The relative junction temperature rise, $\Delta T_j\%$ is defined as $\Delta T_j / \Delta T_{j,dc}$ are also shown in the Fig. 2. The transient time $\tau$ of the junction temperature rise is about 1sec for 95% cooling down.

The steady-state junction temperature rise $\Delta T_{j,dc}$ with respect to $I_{dc}$ is depicted as shown in Fig. 3 with the correlation Eq. (1). For higher DC currents beyond 200mA, $\Delta T_{j,dc}$ can be obtained from the extrapolation using Eq. (1).

$$
\Delta T_{j,dc} = F(I_{dc}) = A I_{dc}^2 + B I_{dc} + C,
$$

where $A = 3.59 \times 10^{-4}$, $B = 0.175$ and $C = 0.315$.

In Fig. 3, based on electrical power $P_e$, the thermal resistance $R_{th,dc}$, which is defined by $\Delta T_{j,dc} / P_e$ and based on the thermal power $P_t$, the $R_{th,t}$, which is defined by $\Delta T_{j,dc} / P_t$ are both shown, where $P_t$ is equal to $P_e-P_o$, and $P_o$ is the optical power of UVLED.

### 2.2 The PWM-Mode

For UVLED driven by PWM-mode currents, its duty cycle $D$ and period $P$ (or frequency) are introduced to realize the correlation.

In Fig. 4, the dynamic junction temperature rise $\Delta T_{j,d}$ of the PWM-mode current of 150mA (the nominal driving DC current) with $D=50\%$ and $P=1$ms, is depicted to show its peak junction temperature rise $\Delta T_{j,p}$ and fluctuation $\Delta T_{j,f}$ as an example when the thermal steady state is reached.

In Fig. 4, the dynamic junction temperature rise $\Delta T_{j,d}$ for PWM-mode current 150mA with $P=1$ms and $D=50\%$. The inset graph is a time enlarged view to show the $\Delta T_{j,d}$ at beginning of a few pulses.
Fig. 5 (a) Comparison between PWM-mode current pulse and the optical output and the dynamic junction temperature rise of the UVLED; (b) Rise time of the PWM-mode current pulse and the optical power pulse; (c) Pulse down time of the PWM-mode current pulse and optical power pulse.

The normalized PWM current, optical and junction temperature pulses are depicted in Fig. 5(a) for comparison. Figs. 5(b) and 5(c) further show an 80μsec pulse rise time for the optical output and a 40μsec pulse rise time for the PWM-mode current. Considering the transient time of the current pulse and the least duty cycle, the minimum period is chosen to be 0.1msec for the best correlation.

The peak junction temperature rise of PWM-mode (ΔTj,p/dc) normalized by DC-mode is correlated with respect to P in Eq. (2).

\[ \Delta T_{j,p/dc} = \frac{\Delta T_{j,p}}{\Delta T_{j,dc}} = a_3 - a_1 e^{-a_2 P^x}, \quad (2) \]

where \( a_1, a_2 \) and \( a_3 \) are the coefficients of correlation as the functions of D. And the fluctuating junction temperature rise of PWM-mode normalized by its peak junction temperature rise (ΔTj,f/p) is correlated with respect P in Eq. (3).

\[ \Delta T_{j,f/p} = \frac{\Delta T_{j,f}}{\Delta T_{j,p}} = b_3 - b_1 e^{-b_2 P^y}, \quad (3) \]

where \( b_1, b_2 \) and \( b_3 \) are the coefficients of correlation as the functions of D. And both \( x \) and \( y \) are optimized to be 0.6.

According to the correlation Eqs. (2) and (3) with \( a_{1-3} \) and \( b_{1-3} \) shown in Fig. 8, ΔTj,p/dc and ΔTj,f/p as functions of D, are also depicted in Figs. 9 and 10, respectively.
The mean junction temperature rise $\Delta T_{j,m}$ average of $\Delta T_{j,d}$ can be approximated by $\Delta T_{j,m} = \Delta T_{j,sm} + (\Delta T_{j,p} - \Delta T_{j,sm})$, where $\Delta T_{j,sm}$ is the average of dynamic part of $\Delta T_{j,d}$, and $\Delta T_{j,p} - \Delta T_{j,sm}$ is the static part of $\Delta T_{j,d}$. $\Delta T_{j,sm}$ can be defined as $\gamma \Delta T_{j,sc}$, where $\gamma$ dependent on $P$ is the area ratio of the dynamic part of $\Delta T_{j,d}$ to $P \Delta T_{j,c}$, such that the normalized mean junction temperature rise can be obtained as shown in Eq. (4).

$$\Delta T_{j,m/p} = 1 - \Delta T_{j,sp} (1 - \gamma).$$

To simplify the correlation with little discrepancy, $D$ is used to replace $P$-dependent $\gamma$ as shown in Figs. 11 and 12, where $\Delta T_{j,m/p}$ is depicted with respect to $P$ ranging from 0.1 to 1000msec. and $D$ ranging from 10 to 90%, respectively.

From the Eq. (2), the normalized peak thermal resistance $R_{th,p/dc}$ can be obtained as shown in Eq. (5).

$$R_{th,p/dc} = \frac{R_{th,p}}{R_{th,dc}} = \frac{\Delta T_{j,p/dc}}{D},$$

where $R_{th,p} = \frac{\Delta T_{j,p}}{(DW)}$, $R_{th,dc} = \frac{\Delta T_{j,dc}}{W}$ and $W$ is the electrical power $P_e$ (or thermal power $P_t$) of the DC-mode driving.

As shown in Figs. 13 and 14, the $R_{th,p/dc}$ is depicted with respect to $P$ ranging from 0.1 to 1000msec. and $D$ ranging from 10 to 90%, respectively.

By defining $R_{th,f} = \frac{\Delta T_{j,f}}{(DW)}$, and $R_{th,p} = \frac{\Delta T_{j,p}}{(DW)}$,

$$R_{th,fp} = \frac{R_{th,f}}{R_{th,p}} = \frac{\Delta T_{j,f}}{\Delta T_{j,p}} = \Delta T_{j,fp}.$$

Thus the correlation of $R_{th,fp}$ with respect to $P$ and $D$ will be the same as $\Delta T_{j,fp}$ as shown in Figs. 7 and 10, respectively.

By defining $R_{th,m} = \frac{\Delta T_{j,m}}{(DW)}$,

$$R_{th,mp} = \frac{R_{th,m}}{R_{th,p}} = \frac{\Delta T_{j,m}}{\Delta T_{j,p}} = \Delta T_{j,mp}.$$

Thus the correlation of $R_{th,mp}$ with respect to $P$ and $D$ will be the same as $\Delta T_{j,mp}$ as shown in Figs. 11 and 12, respectively.
Because the correlation is constructed based on nominal \( I_{\text{pwm}} \) of 150mA with the different P and D, \( \Delta T_{j,p} \) and \( \Delta T_{j,f} \) with respect to a wider \( I_{\text{pwm}} \) range with P=1msec and D=50% is investigated as an example to verify the conformation between correlation and measurement. As shown in Fig. 15, the good agreement with \( \Delta T_{j,p} \) discrepancy about \( \pm 5\^\circ C \) and \( \Delta T_{j,f} \) discrepancy within \( \pm 2.5^\circ C \) verifies the correlation applicable for the studied range of \( I_{\text{pwm}} \) up to 700mA.

![Fig. 15 Comparison between correlation and measurement for \( \Delta T_{j,p} \) and \( \Delta T_{j,f} \) with respect to \( I_{\text{pwm}} \).](image)

To ensure that the maximum junction temperature \( \text{max}(T_{j,dc}) \) recommended by the manufacturer is not exceeded during DC-mode operation, the maximum permissible junction temperature rise \( \text{max}(\Delta T_{j,dc}) \) with respect to the typical room temperature of \( 25^\circ C \), which is also applied to the PWM-mode, \( \text{max}(\Delta T_{j,p}) \), said \( 100^\circ C \) for example. Then, the corresponding normalized maximum permissible pulse current, \( \text{max}(I_{\text{pwm}/dc}) \), depending on its period and duty cycle can be calculated from Eqs. (2) and (3) with the inverse function \( F^{-1} \) of Eq. (1).

\[
\text{max}(I_{\text{pwm}/dc}) = \text{max}(I_{\text{pwm}}) / \text{max}(I_{dc}) = F^{-1}(\text{max}(\Delta T_{j,p}) / \Delta T_{j,\text{p/dc}}). \tag{8}
\]

The shorter P and D, the higher \( \text{max}(I_{\text{pwm}/dc}) \) can be found. However, considering the current crowding and other local heating effects, \( \text{max}(I_{\text{pwm}/dc}) \) should be limited to a reasonable value between 2–3 depending on the LED chip design in practice. The value 2.0 was chosen as shown in Figs. 16 and 17, respectively.

![Fig. 16 Normalized maximum permissible pulse current \( \text{max}(I_{\text{pwm}/dc}) \) with respect to P.](image)

![Fig. 17 Normalized maximum permissible pulse current \( \text{max}(I_{\text{pwm}/dc}) \) with respect to D.](image)

For dimming applications, the proposed correlations also can be used to analyze the Pulse Density Modulation (PDM) current driving with the fixed pulse width \( P_d \) and the modulation periods \( P_d \) analog to the P and D of the PWM. For PDM dimming, the light output resolution is depending on the total number of pulses \( N (= P/P_d) \). \( P_d = P/(ND) = P_d/D \) is the actual period of PDM dimming and \( D_d = P_d/P_d = D \) is the actual duty cycle. Using \( P_d \) and \( D_d \) for the proposed correlations, \( \Delta T_{j,\text{p/dc}} \) can be obtained from Fig. 6. It is found \( \Delta T_{j,\text{p/dc}} \) of PDM (the solid line) is always lower than the PWM’s (the dotted lines) during \( D_d = 10\text{–}90\% \) dimming as depicted in Fig. 18 based on the \( P_d/P_d = 10\% \). The smaller \( P_d/P \) introduces more difference of \( \Delta T_{j,\text{p/dc}} \) between PWM and PDM. At the middle area between \( D_d = 30\text{–}60\% \) and 1 to 10ms pulse width, the difference is the most significant and suggesting the PDM current driving for dimming is superior than PWM from the point of thermal consideration. The reason of lower \( \Delta T_{j,\text{p/dc}} \) for PDM is because of its separated shorter pulses width \( (P_d) \) with the shorter time for junction temperature rising comparing to a continuous longer pulse width dependent on D for PWM.
The ΔT_{j,pd} of PDM current driving can be obtained from Fig. 18 for PWM current driving by replacing D with D_d. Although ΔT_{j,pd} are the same, the lower ΔT_{j,f} can be obtained due to a lower ΔT_{j,pd} for PDM.

**Conclusions**

The power-exponential function of period with 3 coefficients as the functions of duty cycle is proposed to correlate with the normalized peak and fluctuation of junction temperature rise for the nominal PWM-mode current driving within the period and duty cycle range of study. The peak junction temperature rise for PWM is normalized by the DC one for the corresponding DC current, such that the correlation is generalized to be applicable for the pulsed current much higher than the maximum allowable DC current by extrapolation of the correlation of DC junction temperature rise and the DC current. The correlation result comparing to measurement of T3ster with a good accuracy is presented. The normalized mean junction temperature rise, and the peak, mean and fluctuation thermal resistance are further inferred from the correlation. By further combining the PWM-mode with the DC-mode correlations, the normalized maximum permissible pulse current for operation at the maximum permissible junction temperature rise can be found. Using the proposed correlations, the difference between PWM and PDM current driving for dimming is explored and it is concluded that the PDM with lower junction temperature rise and its fluctuation is better than PWM current driving from the point of thermal management.

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**References**


