A Model to Design Light Emitting Diodes Matrix Driven by Constant Current Source

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Abstract— **It is always desirable to operate LEDs within its designed maximum temperature for maximized life. For LEDs driven by a constant current source it is possible to improve LED life by putting more LEDs in parallel to share current and reduce temperature, but the cost would increase. This paper proposes a general LED model to estimate the relationship between temperature, operating current, luminous flux, life and reliability of Light Emitting Diodes. This model can direct LED matrix design with respect to the required parameters. The model would help lighting designers to consider the driving current and number of LED in a lamp matrix in order to achieve the desired light flux, efficacy and life with desired cost. A method involved power electronic technique is proposed to form a dynamic matrix that can response to the changing ambient temperature. This allows the engineer to build the real desired matrix flexibly.**

Keyword: Light Emitting Diode, Model, Reliability, Life, Matrix, Temperature

I. INTRODUCTION

Light emitting diodes provide superior operating life compared to traditional artificial lighting sources. This is one of its strength to its growing share in the lighting market. Present commercial product is able to guarantee a 60000 hours life [1] that operating at the typical power and typical temperature, at least 90% chip would maintain 70% lighting flux at that time. However, if LED is operated outside the designed operating region, especially at high temperature the reliability would drop dramatically and the light intensity would reduce. Research schemes has been carried out to resolve the problem which are mainly oriented to thermal radiation such as mechanical heatsink and package design for better thermal dynamic, and chemically synthesizing high temperature tolerate material. Those researches enhanced the possible application of LEDs but still physically limited by product size and cost. Heatsink occupy spaces and material solution trade off with cost. The current flow would also affect the LED operating life and should be accounted in the design. Other parameters including luminous flux and efficacy would contribute to the performance of a lamp and might be required to achieve a certain level. This paper proposes a model that illustrates the temperature and current effect on reliability. Lighting engineers could solve the overheat problem by electronic means with better LED matrix arrangements. The model is tested with data provided by manufacturers and an application example is demonstrated.

II. BACKGROUND

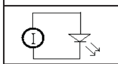
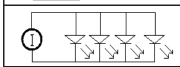
Luminaries generate heat. The heat generated from the core of the light, deteriorating itself steadily and heat up the surrounding. As conventional light source generate heat from its tungsten or discharging gas, heat would generate from the P-N junction of a LED. Due to the tiny chip area, the heat resistance from the core to heatsink of high power LED is higher than gas discharge lamp.

For closely packed LED, the heat emitted by the LED matrix affect each other. For lighting purpose it is unavoidable to pack high power LED high density. Therefore the operating temperature may rise over the designed one and shorten the life.

Nowadays LED drivers are constant current source power supplies. The current is programmed. Examples of popular current settings are 350mA and 700mA. Apart from using bigger heat sinks another way to reduce deterioration is to put in parallel LED devices in the matrix driven by a constant current source (Table I). When more LEDs are put in parallel the current through each LED is smaller. As the current is smaller life of each LED is extended, at the expenses of more devices. Efficacy may be different according to the characteristics of the LED. The design of the LED matrix is a balance on life, efficacy and number of parallel devices. This paper proposes a general model that can be used to design the LED matrix.

TABLE I.

RELATIONSHIP BETWEEN LED NUMBER IN A MATRIX TO THE PERFORMANCE PARAMETERS

	Number of LEDs	Per Chip Current	Per Chip Temp	Life	Efficacy	Initial Cost
	1	I	Higher	Shorter	Lower	Lower
	N	I/N	Lower	Longer	Higher	Higher

III. PROPOSED MODELS

A.The Model of Light Intensity to Operating Condition

Lighting flux of LED would be affected by forward current and temperature. Ideally, the relationship of the relative light flux and junction temperature can be represented by the formula below:

$$\Phi_{relative} = \Phi_{flux@K=0} \times e^{(T/T_C)} \quad (1)$$

In practice flux emitted from the junction would saturate under low temperature, due to the lowered semiconductor conductivity. In the non-saturated region the relative flux can be reflected by

$$\Phi_{relative|Temp} = \Phi_{T=SatPt} \times e^{((T-T_{sat})/T_C)} \quad (2)$$

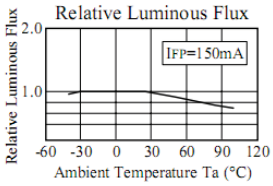


Figure 1 Luminous Flux Saturate at low temperature[2]

Where T_c represents the temperature dependency. The higher T_C the more the LED flux is affected by temperature. Heat emitted from the junction would distribute to the soldering point through the package. Then it spreads to the surrounding through the printed circuit and the heatsink. The heat radiation equation would be applied to estimate the junction temperature with ambient temperature.

$$T_j = T_{ambient} + P_{LED} \times R_{j\,to\,ambient} \quad (3)$$

$$R_{j\,to\,ambient} = \sum R_{radiattion\,path} \quad (4)$$

Operating current is the main factor on flux emission. Behavior of the lighting flux versus forwarding current highly depends on the junction chemistry. In general for most chemistry the light flux to current can be represented by

$$\Phi_{relative|current} = K \times I^m \quad (5)$$

Commercialized high power white lighting LEDs mainly adapt the lnGaN/YAG chemistry. The P-junction is Gallium and Indium doped and the N-junction is Nitrogen doped. This junction release 450nm blue light and the Yttrium Aluminium garnet layer on the package would activate by the light and emits yellow light. The mixture is milky white light visually. One character of this chemistry is the luminous efficiency is higher at lower current. [3]

Combining the equations of current and temperature a model indicated the relationship between current, temperature and luminous flux can be made

$$\Phi_{relative} = \Phi_{relative|current} \times \Phi_{relative|temp} \quad (6)$$

This model is applied to represent the products of different brands.

B.Reliability Model

Reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time. It can be quantified by probability measurement. It is identified by

R(t) = the probability of surviving (not failure) at age t

$R(t) = 1 - f(t)$ and $f(t) = Nf(t)/No$

Mathematically reliability could be represented in Arrhenius equation [5].

$$R(a) = \exp(-\lambda t) \quad (7)$$

λ is the failure rate. For LED degradation temperature dependent phenomena related to atomic and molecular scale mechanism, such as diffusion, precipitation and fatigue, atom must surmount an energy barrier, E_a before the chemical reaction. The activation over the energy barrier can be expressed by a probability factor, the Boltzmann factor.

$$\exp(-E_a/kT) \quad (9)$$

Therefore

$$\lambda = C \times \exp(-E_a/kT) \quad (10)$$

Where C is a constant.

To estimate the failure rate at a typical temperature

$$\lambda_T = \lambda_{T,REF} \exp\left(\frac{-Ea}{k} \times \left(\frac{1}{T_{REF}} - \frac{1}{T}\right)\right) \quad (11)$$

$\lambda_{T,REF}$ is the fundamental failure rate which can be obtained by statistic data and the λ_T is the estimated failure rate of the typical temperature. For fixed junction temperature, the reliability is current dependent. Similar to the temperature case, the failure is can be estimated by

$$\lambda_I = \lambda_{I,REF} \exp\left(\frac{-Ea}{k} \times \left(\frac{1}{I_{REF}} - \frac{1}{I}\right)\right) \quad (12)$$

where λ_I is the failure rate at a typical current. Since the required functions of the system can be changed, the shape of the reliability would vary. In the situation of LED, it is the percentage of units (B) still emitting a certain percentage of their original light flux (L). Therefore a shaping factor should be added to the Arrhenius equation.

$$R(a) = \exp(-\lambda t^{\beta}) \quad (13)$$

The overall reliability factor combined the effect of temperature and operating current is

$$\lambda = \frac{\lambda_T \times \lambda_I}{\lambda_{REF}} \quad (14)$$

While λ can be obtained by statistic, the larger the database, the higher the accuracy.

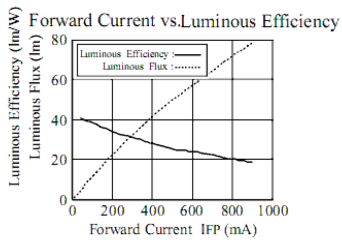


Fig 2 Luminous Efficacy decreases when current increases[4]

C.Estimating the Life

Here a life model is derived from the reliability model, with the limited statistical data that could be provided my most manufacturers. Life is defined by the time that a system takes to unable to perform its function. In the model it would be defined as the time that the LED takes for its reliability reduce to the required value. Since LED would also decay other non electronic operational factor, a maximum limit would be added according to the data given by the manufacturer.

The life equation derived from the reliability equation is

$$life = \sqrt[\beta]{\frac{(\ln(Reliability_{req}))}{-\lambda - \lambda_{max}}} \quad (15)$$

λ_{max} is the failure rate at the confident life provided by the manufacturer. The reliability of LED is not guaranteed at any operational condition expired this life.

IV. ADAPTING THE MODEL TO REAL LEDS

The detail luminous flux and reliability model is applied to a LED available in the market. Parameters and reference points are obtained from the datasheets. The data estimated from the model is compared to the typical experimental data which available from the datasheet.

In the model of luminous flux versus forward current and thermal pad temperature, the testing point and typical point was taken as reference. 6 brands were tested and in all situations the model fits the real situation well. Maximum error is smaller than 2.5%.

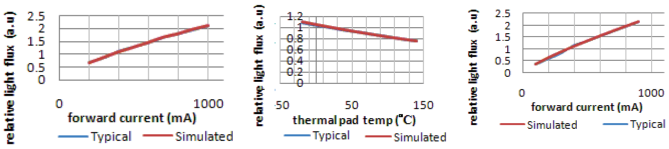


Fig 3. The comparison between manufacturers data and models
←flux vs current ↑ flux vs temperature (Luxeon Rebel, InGaN types) [6]
→flux vs current (Everlight 5W)[7]

The reliability model is hard to verify as huge amount of statistic for years is required to obtain the long term reliability. One model was built according to the data in a paper published by one manufacturer, using the first 6000 hours statistic to predict the reliability thereafter [8]. The reliability is transformed into life and could be shown in a 3 dimensional graph.

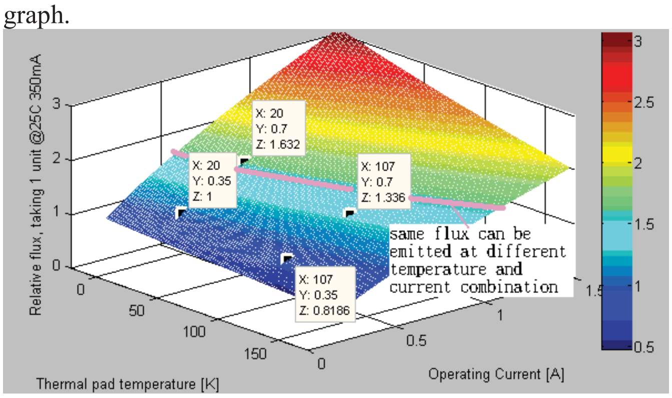


Fig 4a Luminous Model of Luxeon K2

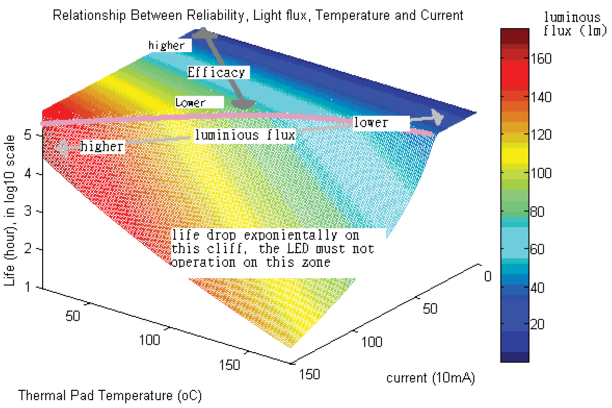


Fig 4b Life and Luminous Model of Luxeon K2

V. A SIMULATED LIGHTING SOLUTION

In a typical lighting requirement, the lamp can be assembled with different number of LED. Assume that the LED matrix is driven by a fixed standardized current source, the number of LEDs to be used would depends on flux, temperature and life. If current could be tailor-made, the current of one LED can be estimated by

$$I_{@LED} = \sqrt[m]{\frac{\Phi_{required}/N}{\Phi_{T=sat} \times e^{((T-T_{sat})/T_C)}}} \qquad (16)$$

The following example demonstrates how the life and flux be effected in a given designed operating situation.

Designed flux: 300lm Luminaire efficiency: 80% Package Thermal Resistance = 30K/W Ambient temperature = 60 Constant Driving current = 2.8A. Confident life =60 000hours. B = 10, L = 90

The performance of the LED matrix of different arrangement is estimated by the model proposed above:

TABLE II.

THE ESTIMATED PERFORMANCE VERUS NUMBER OF THE LED

N	1	2	3	4	5	6	7
Predicted Life($\log_{10}$hrs)	0.25	2.68	4.03	4.76	4.78	4.78	4.78
Chip Current(mA)	2800	1400	933	700	560	467	400
Total Luminous Flux	203	243	271	292	310	325	338

Utilizing conventional method referring to datasheet only, it is estimated 4 LED satisfied the requirement. Due to the luminous flux is deteriorated by temperature, in practice the required light cannot be satisfied. With the model, it is obtained that the requirement could be perfectly achieved with 5LED placed in parallel.

VI. A METHOD TO OBTAIN THE DESIRED MODEL

The model proposed enables the engineer to figure out the performance parameter of specific LEDs and number of LED chips necessary. However in practice it is common to drive LED series thus the output power could be higher, in order to achieve higher efficiency. This restricted the flexibility design. For example, a serial of 8 LED can only have multiple of 16, 24… when they are connected in parallel. If the model suggested 9LED is required, simply putting the 8x2 LED series in parallel would be wasteful. And using 8x1 serial would not meet the required life time. And putting series of different number of LED in parallel is impossible, since the V-I curve of diode is exponentially increased.

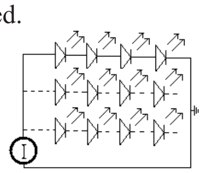


Fig 5a for serially connected LED, duplicate the series would be costly

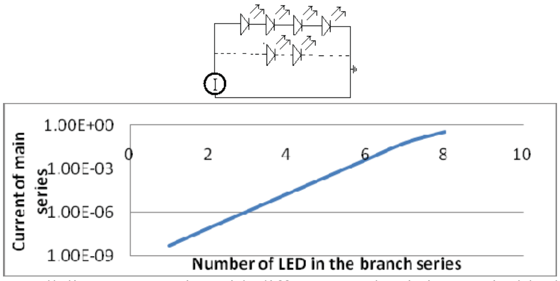


Fig 5b paralleling LEDs series with different number is impracticable that the V-I characteristic is exponentially increased

Here a dynamic matrix is proposed to aid lighting engineers to obtain their desired model. A MOSFET controlled by a simple MCU would be added to the branch series to control. The MCU implemented with an ADC module would control the current flow in the branch with respect to the feedback temperature.

Since the LED drivers that could be purchased in the market are not ideal current source, the driver cannot provide constant current that response fast enough to the switch. LED Drivers purchased are tested, most converter are driven by 100 kHz PWM pulse and the transient response are in the order of millisecond. The slow response would result in overvoltage to the branch LEDs and damaging them. Further improvement should be conducted. A simple buck converter was added to step down the voltage for the branch serial.

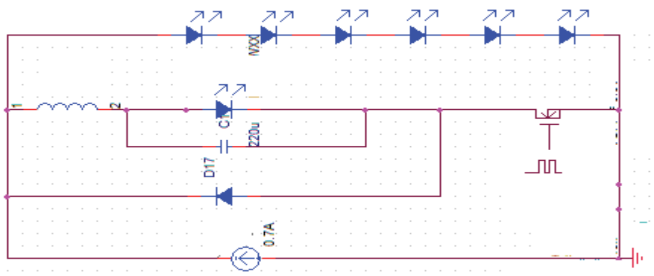


Fig 6 The circuit of LED lamp with bucked protection branch serial

When the duty cycle ranges from 0 to 40%, the main serial current could be reduced in proportional to the duty cycle. The relationship between the duty cycle to the performance parameters could be figured out by integrating the model developed above, I-V characteristic of LEDs and buck converter characteristic. An operation model was build for an example. The system configuration is list below.

TABLE III

THE SPECIFICATION OF THE EXAMPLE LED LAMP

Brand of LED	Bargaining Brand of Taiwan
Rated power	1watt x 6
Main serial	6LED
Branch serial	1LED
Package Thermal Resistance	10K/w
Heatsink thermal resistance	25K/w
LED Driver	Famous European Brand, 100kHz, I_{rated}=0.375A, $T_{response}$ = 4ms

The simulated performance could be shown in 3-D graphs.

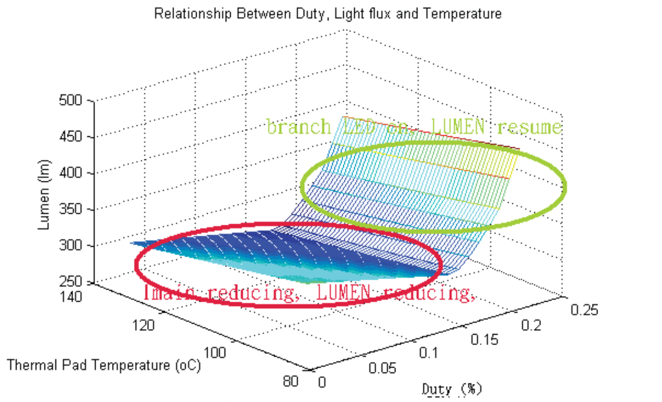


Fig 7 The overall Light flux versus Temperature and duty cycle

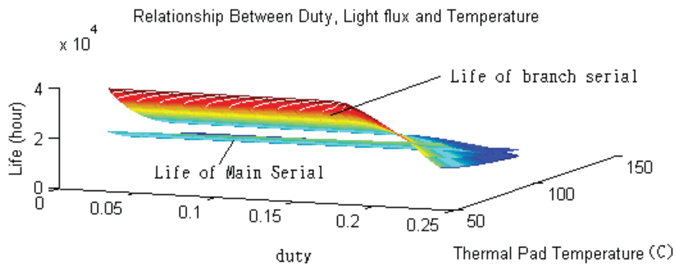


Fig 8 The Life of LEDs versus Temperature and duty cycle

The result is appreciated. Before the branch LED reached its threshold voltage, and the main serial can be cooled while the duty is increasing. In this region the light flux is reduced as a trade off to the life. When the branch serial started to conduct, the light flux is resumed. In this mode, the light flux can be fully compensated and even higher than the original. And the package is heated thus life improvement is reduced. Engineer could program the controller to maintain the flux or the life. The compensate capacity is proportional to the number of branch LED. Further research is doing on and modeling the situation of duty cycle higher than 40%.

VII. CONCLUSIONS

A model is developed which includes important LED parameters necessary to design an LED matrix. The parameters are light intensity, current, temperature, reliability and life of LED. The model is general enough to apply to different types of LEDs manufactured by different manufacturers using different materials. The required LED number and its life can be obtained with operating condition and desired luminous flux is given. The relationships among the parameters are illustrated in graphs and the effect of different choices of the LED matrix shown. A circuit involved a simple buck converter is proposed to realize the desired matrix found. The matrix can be controlled with respect to the changing ambient temperature. The controlled algorithm can be flux orientated that the light flux can be maintained while temperature increased, or life oriented that the life can be maintained. The model combine the circuit would help lighting engineers and LED utilization designers to find out the best LED matrix that balanced between life and the number of LED units and produce the best economical solution with a high degree of freedom.

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