Practical method for measurement of AC-driven LEDs at a given junction temperature by using active heat sinks

Yuqin ZONG [1], Pei-Ting CHOU [2], Min-Te LIN [2] and Yoshi OHNO [1]
[1] National Institute of Standards and Technology, Gaithersburg, Maryland, USA
[2] Industrial Technology Research Institute, Chutung, Hsinchu, TAIWAN

ABSTRACT

Alternating-current (AC) driven high-power light-emitting diodes (LEDs) have become available and introduced into solid-state lighting (SSL) products. AC LEDs operate directly from a mains supply with no need of drivers, and thus can simplify the design of SSL product and potentially increase product's reliability and lifetime. Similar to direct-current (DC) LEDs the optical and electrical properties of AC LEDs are strongly dependent on the LED junction temperature. In addition, the instantaneous junction temperature of an AC LED changes rapidly within an AC power cycle. Accurate measurement of AC high-power LEDs is required for quality control and product qualifications such as the US Energy Star. We have developed a simple, robust method for measurement of high-power AC LEDs at any specified junction temperature under a normal AC operating condition. An active heat sink is used for setting and controlling the junction temperature of the test AC LED. By using this measurement technique, the measurement of an AC LED also obtains the thermal resistance between the LED junction and the LED heat sink.

Keywords: AC LED, Active heat sink, High-power LED, Junction temperature, Measurement method.

1. INTRODUCTION

Various new high-power light-emitting diodes (LEDs) are being developed and used in solid-state lighting (SSL) products with the rapid development of SSL technology. LEDs and SSL products are temperature sensitive to thermal operating conditions. Thus it is essential to properly define and control the thermal condition of an LED in order to obtain accurate and reproducible measurement results. We developed a practical method for measurement of direct-current (DC) driven high-power LEDs at any specified junction temperature by using active heat sinks [1]. This measurement method is to be used in research, quality control, design of SSL products, and government regulations (such as the US Energy Star).

DC LEDs are designed to operate at a constant DC current and thus need electronics (LED drivers) in a SSL product to convert the AC power from a mains supply to a constant DC current source. The AC to DC power conversion consumes 10 -20 % of total electricity of the SSL product and may also lower reliability and shorten lifetime of the SSL product. To address the power conversion issue with the DC LEDs, alternating-current (AC) driven LEDs were developed in recent years and have been introduced into SSL products [2]. Unlike DC LEDs, AC LEDs are designed to operate at a constant AC voltage and can be directly plugged into a mains supply (e.g., 120 V AC, 60 Hz) without the need of any electronics (as shown in Figure 1). Compared to DC LEDs, AC LEDs simplify the design of SSL product and can potentially increasing reliability and lifetime. AC LEDs have obvious advantage in some general lighting applications such as lamp replacement LED products where LED drivers often operate in a very high temperature.

Figure 1. Photo of an AC LED plugged into the mains supply

The optical and electrical parameters of an AC LED are also highly sensitive to its thermal operating condition. In addition, the forward voltage, the forward current, and the junction temperature of an AC LED change in an AC power line cycle. Based on our previous work [1], we have developed a simple and robust method for measurement of AC LEDs, with which AC LEDs can be operated at any specified junction temperature for optical and electrical measurements under a thermal equilibrium condition to achieve accurate and reproducible measurement results.

2. PRINCIPLE

The configuration of AC LED chips have various designs, depending on the manufacturers, such as series type [3], bridge type [4, 5], ladder type [6], and so on. However, the principle can be simplified (for the measurement purpose) as that shown in Figure 2. An AC LED is composed of two DC LED arrays, which work alternatively in a complete AC power cycle. The sum of forward voltage of the LED array is equal to the instantaneous voltage of the AC power supply, and the LED array does not turn on until the instantaneous voltage reaches the threshold "on" voltage. Figure 3 shows the instantaneous forward voltage and the forward current of a 110 V, 60 Hz AC LED during a complete AC power cycle. The total "on" time of an AC LED is approximately 50 % of a complete AC power cycle time, and the light output frequency is 120 Hz.

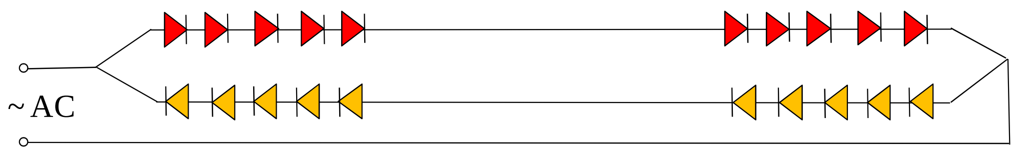

Figure 2. Illustration of the design of an AC LED

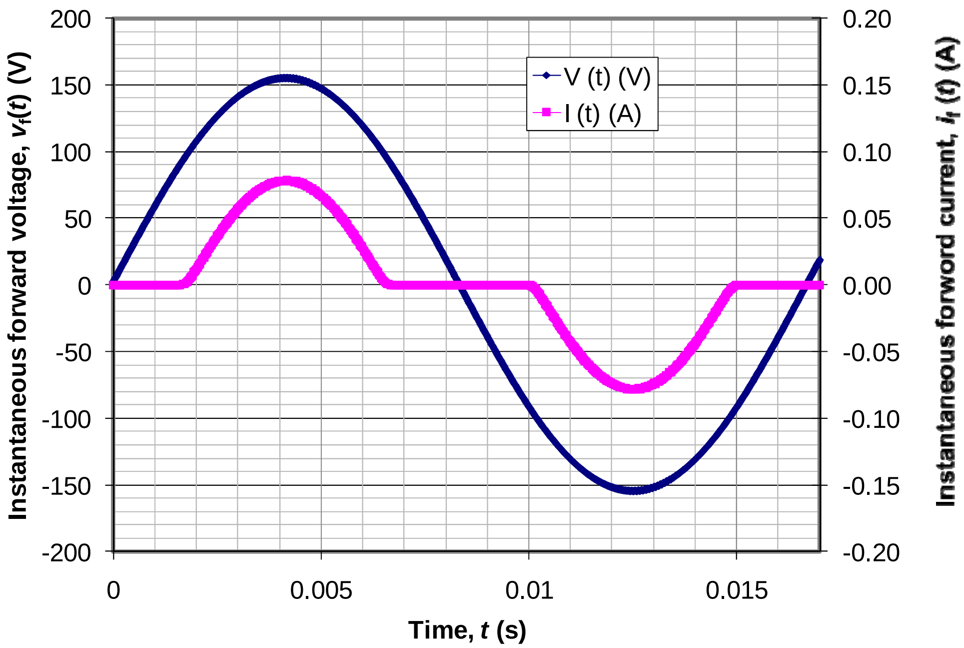

Figure 3. Instantaneous forward voltage, $v_f(t)$, and instantaneous forward current, $i_f\,(t)$, of a 110 V AC, 60 Hz LED.

For an AC LED at a fixed instantaneous forward voltage, $v_f(t)$, the instantaneous forward current, $i_f(t)$, increases as the AC LED junction temperature increases. Thus, an instantaneous forward current, $i_f(t)$, at a fixed instantaneous forward voltage can be used to monitor the change of the instantaneous junction temperature, t_j, of an AC LED. In theory, by simply replacing the forward voltage of a DC LED with the instantaneous forward current of an AC LED as the feedback parameter for controlling the junction temperature, the same method developed for the measurement of DC LEDs [1] can be used to measure AC LEDs. In practice, however, this method does not work with AC LEDs. During operation of an AC LED, its electrical/optical values and the thermal condition (*e.g.* the junction temperature) change constantly. The measurement errors are too large for the instantaneous forward current of an AC LED. The large measurement errors mainly come from three sources: 1) the synchronization error between the voltage measurement and current measurement, which is critical because the applied voltage changes rapidly, 2) the noise on the AC voltage of the power supply. Note that voltage noise is amplified many times to current noise due to the LED's steep voltage versus current characteristics (the *V-I* curve), and 3) the digital multimeter; the faster the measurement speed, the larger of the measurement uncertainties.

To overcome the difficulty in measuring the instantaneous forward current, $i_f(t)$, we choose to measure the root mean square (RMS) forward current, $I_f(n)$, averaged over half of an AC power cycle to monitor the change of the RMS junction temperature of the AC LED. Because the AC LED has only approximately 50 % "on" time, the RMS forward current, $I_f(n)$, can be easily measured without the need to synchronously measure the instantaneous LED forward voltage.

The principle of the simple method for measurement of AC LEDs is shown in Figure 4. The measurement procedures of this method are as below: (1) mount the AC LED on a temperature-controlled heat sink (with a TE cooler) by using a metal core printed circuit board (MCPC board) or any other thermal connection techniques, (2) set the temperature of the heat sink equal to the desired junction temperature, T_j , and wait for the LED (not turned on yet) to stabilize thermally, (3) apply the specified AC voltage from zero phase to the AC LED and measure the first half-cycle RMS forward current, $I_f(0)$, (4) as the LED is operated on the AC power and is heated up, adjust (lower) the heat sink temperature, T_s, so that the measured RMS forward current, $I_f(n)$, equals to initial $I_f(0)$ obtained in step (3) and thus the same T_j is maintained when the LED reaches the thermal equilibrium, (5) measure the electrical, radiometric, photometric, and colorimetric quantities of the AC LED, and (6) power off the AC LED to finish the measurement. Using a programmable temperature-controlled heat sink, the entire measurement procedures can be fully automated.

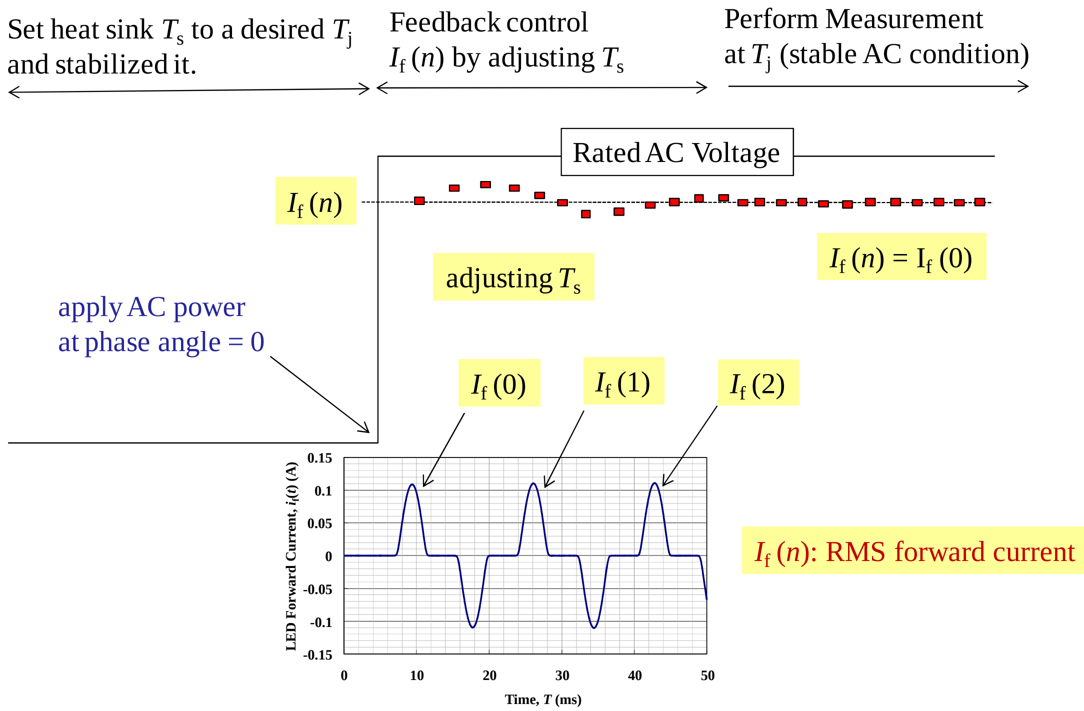

Figure 4. Principle of the practical method for measurement of AC LEDs

The above procedure used for setting and controlling the junction temperature of an AC LED is similar to that used for the measurement of a DC LED [1]. A temperature-controlled heat sink is used to set and control the AC LED to a specified junction temperature, T_j , and all electrical and optical quantities of the AC LED are –measured in a steady AC operation under a thermal equilibrium condition. Once the AC LED is stabilized in this condition, various photometric measurements can be made with the existing measurement facilities used in the lighting industry, such as those used for measurement of discharge lamps, including integrating spheres, gonio-photometers, and spectroradiometers (array or scanning type).

Fast measurement is required only for the electrical quantity, $I_f(n)$, which is measured and used for calibration and control for each AC LED immediately before the optical measurement. Therefore, variation of the $I_f(0)$ versus T_j relationship between individual LEDs and change of the $I_f(0)$ versus T_j relationship for a particular LED over time does not matter. The AC LED mounting method and the thermal contact between the AC LED and its heat sink are also largely irrelevant to the measurement results because the junction temperature is controlled. Furthermore, the thermal resistance between the AC LED junction and its heat sink surface is obtained, which is often of great interest.

3. EXPERIMENTAL MEASUREMENT RESULTS

Several LEDs from two different manufacturers are measured to validate the measurement method. Figure 5 shows an example of the relationship between the RMS forward current, I_f, and the heat sink temperature of an AC LED from 25 °C and 45 °C. The I_f is a linear function of the heat sink temperature within the temperature range and also a linear function of the LED junction temperature assuming both the thermal resistance and the LED efficacy are constant within this temperature range.

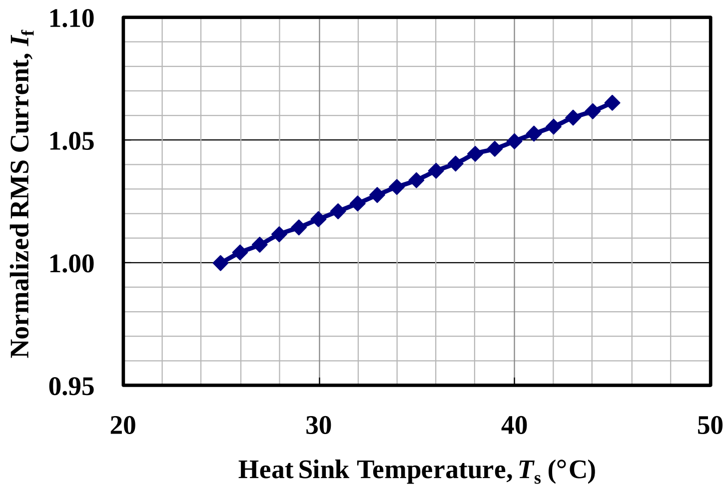

Figure 5. Relationship between the LED RMS forward current, I_f , and the heat sink temperature, T_j

The heating curve of an AC LED operated on a 60 Hz, 110 V AC power is shown in Figure 6. The horizontal axis shows the count of power line cycles. The AC LED is mounted on a 25 °C temperature-controlled heat sink. The current of the AC LED is measured by using a fast digital multimeter with a measurement speed of 50000 samplings per second. The junction temperature of the AC LED rises rapidly as shown by the rapid rising of the RMS forward current. The junction temperature of the LED rises approximately 25 % of the total rise within the first AC power cycle, which is significant.

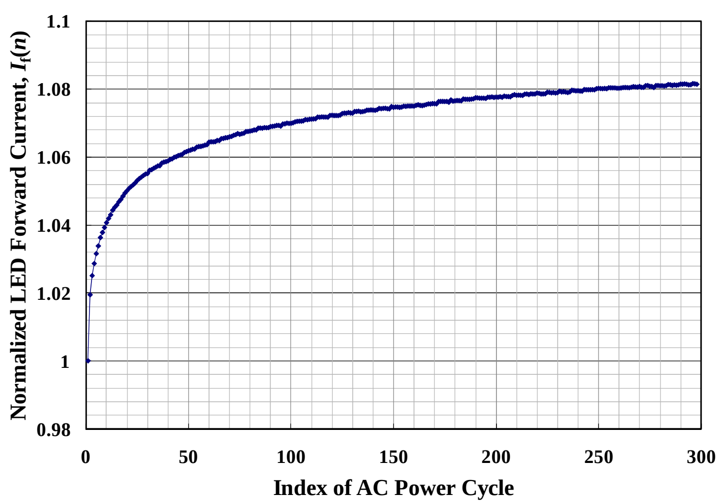

Figure 6. Plot of a heating curve of an AC LED.

4. DISCUSSION

With the practical method described in Section 2 and illustrates in Figure 4, an AC LED is already heated up slightly during the first half power cycle, thus the forward RMS current measured at the first half power cycle, $I_f(0)$, is higher than the "true" forward RMS current at the set junction temperature. Consequently, the junction temperature of the AC

LED is actually feedback-controlled to a slightly higher temperature than the set temperature. Thus, we may call the set junction temperature to be the "nominal" operating junction temperature of the AC LED. Nevertheless, the difference between the set junction temperature and the actual operating junction temperature does not depending on the heat sink and mounting methods, which makes the temperature difference be constant and the measurement results be reproducible and universal.

It is possible to control the junction temperature of an AC LED more accurately to the set junction temperature if the instantaneous forward current $i_f(t)$ can be measured accurately at the very beginning of the first half power cycle and at exactly the same phase point in the following power cycles for the feed back control. Such measurements can be made by using a so-called "source-measure unit (SMU)", which is also used for the measurement of DC LEDs as described in Reference 1. A SMU can be programmed to generate a set of discrete voltages to simulate an AC power and to measure each corresponding instantaneous forward current of an LED. We have performed such measurements using a SMU. Unfortunately, the speed of existing SMUs currently available is too slow, which limits the frequency of the generated AC power waveform. If the LED is operated at a frequency lower than normal 60 Hz, it might introduce additional uncertainty in optical measurements. This SMU-based method may be practical if higher speed instruments become available.

5. SUMMARY

We have developed a simple and robust method for measurement of AC-driven LEDs. By using a temperature-controlled active heat sink, an AC power supply with phase control, a fast digital multimeter (or a high-accuracy oscilloscope, or a high-accuracy fast digitizer), and existing AC instruments, AC LEDs can be set at any junction temperature and measured in a steady AC operating condition in thermal equilibrium. This method can be applied to any type of AC LEDs, any LED shapes, any heat sinks, and any mounting techniques. This method not only allows measurement of optical quantities at given junction temperature, but also determines the thermal resistance between the junction and the heat sink. The measurement results are insensitive to measurement noise, and are irrelevant to mounting method and thermal resistance. By using this practical method for measurement of high power AC LEDs, reproducible results with small uncertainties can be achieved in optical measurements. The measurement uncertainties of AC LEDs will be analyzed and discussed elsewhere in the future.

Further research is planned for using a source-measure unit to measure AC LEDs at normal 60 Hz frequency and to control the LED junction temperature more accurately to the set temperature.

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