Application Note

LED Lighting Test: Beyond the Normal Methods

58158-SC LED Lighting In-Line Test System

Keywords: LED test, luminous flux, CRI, CCT, flicker, spatial distribution

Chroma Systems Solutions, Inc.

Title: LED Lighting Test: Beyond the Normal Methods
Product: 58158-SC LED Lighting In-Line Test System

Scope

LED lighting is well known as an energy saving and eco-friendly light source technology, and it is widely believed that these features will make LED the dominant technology in the lighting market ultimately. However, the current relatively high price of LED lighting products has become an obstacle to market adoption. Additionally, in the early development stage of the technology, inconsistent specification claims, uncertain performance quality, and unpredictable reliability are also concerns of consumers. Several standards have been published to provide a baseline for evaluating LED lighting performance. Unfortunately, these standard measurement methods only focus on measurement accuracy; other factors like test speed, tool sizes, and convenience of loading/unloading are not taken into consideration. Thus, standard measurement methods tend to be restricted to laboratory use raising the question: can product quality be assured if only limited samples are tested in a laboratory? Is there an alternative method specifically designed for production testing? The answer is now yes.

In this article, an innovative test method is covered in depth. This method is capable of measuring the key performance parameters; total luminous flux, CRI, CCT, flicker, and even spatial distribution. Several experiments have been prepared, showing that the measured values using this method correlate to an integrating sphere's measured values with a high degree of accuracy. Real production test data from an LED lighting manufacturer is provided, and the latest U.S CALiPER summary report is discussed. Both of these imply the necessity for production testing. A few features of implementation of this method are; compact size, high test speed, and high cost effectiveness. These factors combined with the ability to easily integrate with automation systems illustrate that 100% production testing is feasible.

Standard Laboratory Measurement Methods

There are several standards that relate to LED lighting products. Among these standards, Illuminating Engineering Society's (IES) LM-79 is the most widely used for electrical and photometrical measurement. LM-79 describes the IES approved method of standard procedures for electrical and photometrical parameters measurements, such as total luminous flux, electrical power, luminous intensity distribution, and chromaticity of solid state lighting products for illumination purposes. For the optical parameters measurements, two methods are introduced: the goniometer method and the integrating sphere method (see Figures 1 and 2). As standard methods, the measurement accuracy and reproducibility are the main focus; other factors such as test speed, tool sizes, and convenience of loading/unloading a DUT (device under test) are not taken into consideration. For example, it can take anywhere from minutes to hours for a single DUT measurement when using the spatially scanned goniometer method, depending on the scan resolution. Additionally, the tool size of both methods is also not easily ignored. For example, to measure a 4 feet LED tube, the integrating sphere must be larger than 2 meters in diameter. Finally, the loading and unloading of the DUT for a goniometer or integrating sphere is also noticeably inconvenient. Therefore, although the standard methods may provide very accurate measurement values, they are more suitable for laboratory use and are not practical for application on a production line. With a limited number of sample tests in the laboratory, the quality of LED lighting products remains questionable.

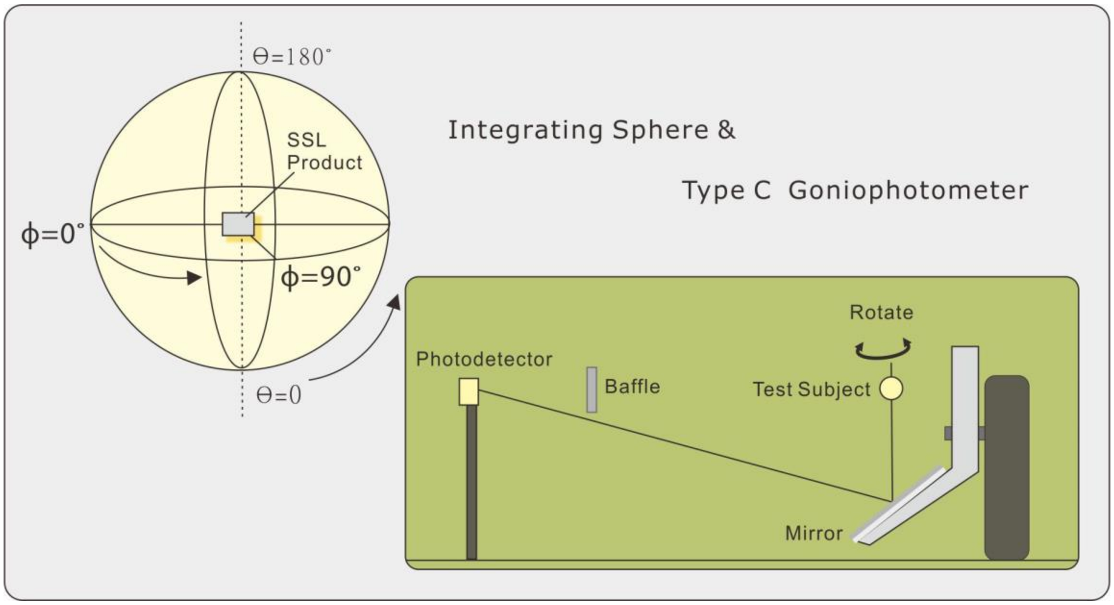


Figure 1: Goniometer test method

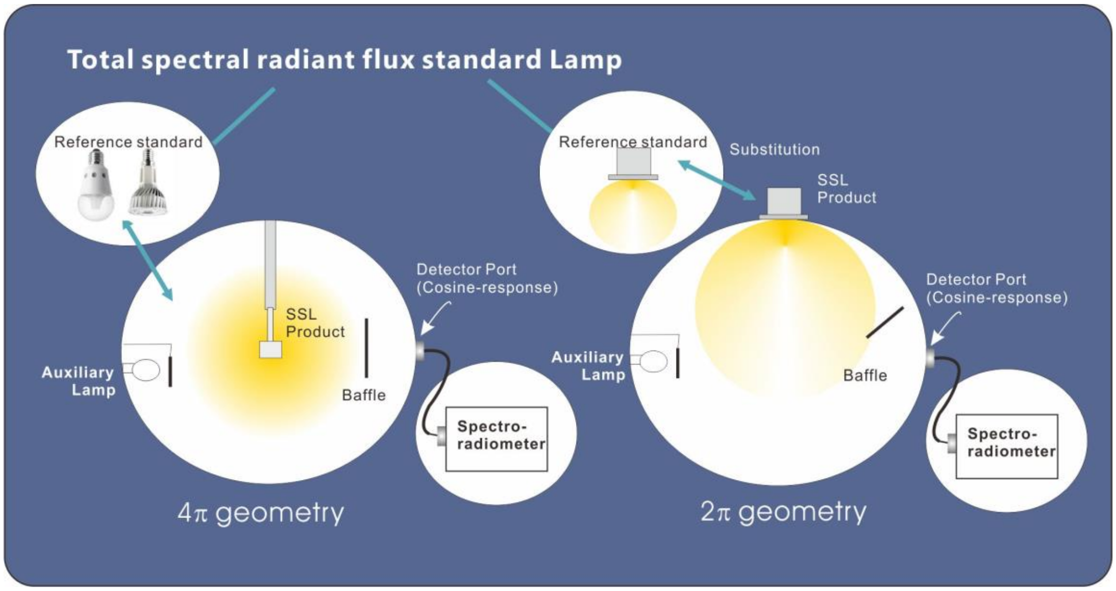


Figure 2: Integrating sphere test method

An Innovative Production Testing Method

Considerations for production testing may be different from the standard test method. While accuracy is the only concern of the standard test method, the footprint of tooling, test speed, convenience of operation, and the overall test cost are also important factors for production tests. The main purpose of production testing is to assure product quality and consistency. Measurement accuracy is important, but allows more tolerance than the standard method. If a test system satisfies criteria corresponding to compact tool size, high test speed, high cost effectiveness, and measured values that correlate closely to the laboratory's standard measured values, then the test system is suitable for production testing.

One possibility for meeting these criteria is to appropriately arrange photo detectors surrounding the DUT, so that the size of the test system is just slightly larger than the DUT. The compact size of the tool makes it easier to operate, and also makes it easier to combine with automation machinery. However, to measure adequate optical power output from the DUT, the number of photo detectors must be enormous, and so is the cost involved. If there are any low cost big-area detectors available, the number of photo detectors can be reduced significantly, and the cost effectiveness target can be met.

Theory

If the tool were to use mono-crystalline silicon solar cells as photo detectors, the larger area of the cells may reduce the number of required detectors while still maintaining adequate coverage. The price of commercially available solar cells is also competitive. The typical spectral response of a commercially available mono-crystalline silicon solar cell is shown in Figure 3. It's not hard to determine that it has excellent spectral response for the spectrum range of all visible LEDs known today. Also, the Isc, short circuit current, of a solar cell is a function of the radiation, which is the total radiant power received over the active surface of the solar cell. Therefore, by measuring the short circuit current with the known absolute spectral response of the solar cell and spectral luminous intensity distribution of the test LED, the total radiant power of the test LED can be calculated mathematically.

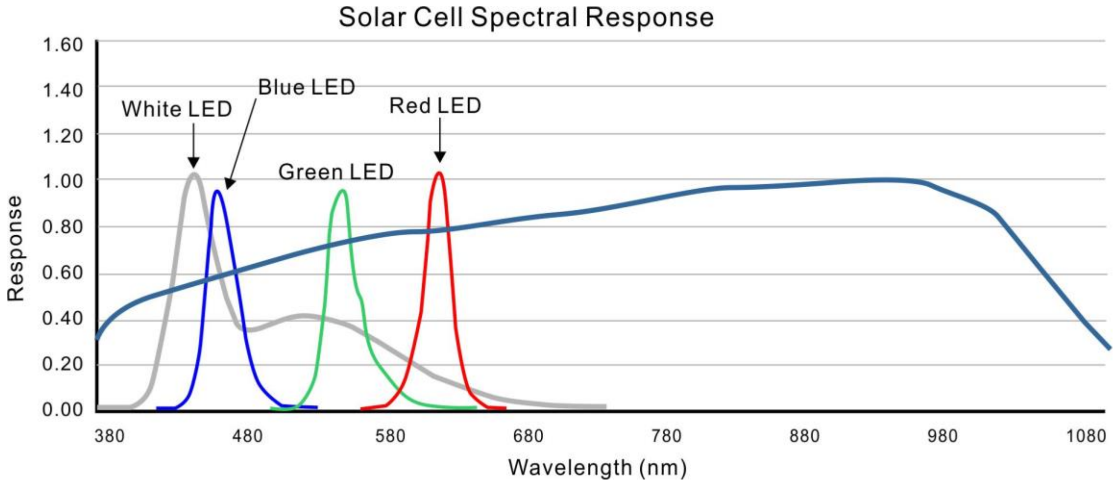


Figure 3: Mono-crystalline silicon solar cell spectral response

The short circuit current of a mono-crystalline silicon solar cell with LED light shining on it, in theory, can be expressed as below:

$$Isc_{\_SolarCell} = \int_{\lambda 1}^{\lambda 2}\int_{\phi=0}^{2\pi}\int_{\theta=0}^{\pi} I_{\_LED}(\lambda,\theta,\phi)\cdot SR_{\_SolarCell}(\lambda,\theta,\phi)\cdot \sin(\theta)\,d\lambda\, d\theta\, d\phi \tag*{[1]}$$

Where:
λ1-λ2 is the spectral distribution range of the test LED
Isc_SolarCell is the short circuit current of the solar cell
I_LED(λ,θ,ψ) is the relative spatial radiant intensity of the test LED per wavelength.
SR_SolarCell(λ,θ,ψ) is the absolute spectral response of the solar cell

If it is assumed that the relative spectral distribution of the test LED light shining on the solar cell is spatially uniform, and the absolute spectral response of the solar cell across the active surface is also spatially uniform, then equation [1] can be expressed as:

$$Isc_{\_SolarCell} = k_1 \int_{\lambda 1}^{\lambda 2} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} Ir_{1\_LED}(\lambda) \cdot Ir_{2\_LED}(\theta,\phi) \cdot SR_{\_SolarCell}(\lambda) \cdot \sin(\theta) \, d\lambda \, d\theta \, d\phi \qquad [2]$$

Through some mathematical derivations, the radiant power of the test LED light shining on one solar cell can be expressed as:

$$P_{\_LED} = k \frac{Isc_{\_SolarCell}}{\int_{\lambda 1}^{\lambda 2} Ir_{1\_LED}(\lambda) SR_{\_SolarCell}(\lambda) d\lambda} \int_{\lambda 1}^{\lambda 2} Ir_{1\_LED}(\lambda) d\lambda \qquad [3]$$

And the luminous flux of the test LED can be expressed as:

$$P_{\_LED} = k \frac{Isc_{\_SolarCell}}{\int_{\lambda 1}^{\lambda 2} Ir_{1\_LED}(\lambda) SR_{\_SolarCell}(\lambda) d\lambda} \int_{\lambda 1}^{\lambda 2} Ir_{1\_LED}(\lambda) d\lambda \qquad [4]$$

Where V(λ) denotes the luminosity function.

The implementation of the test system is to appropriately arrange solar cells around the DUT (hereafter referred to as the PV module). The arrangement is determined according to the LED lamp form factor. For example, for a light bulb form factor, the implementation is a square box; for an LED tube, the implementation is a hexagon box (see Figures 4 and 5).

The total luminous flux for the implementation is the sum of the luminous flux received by each solar cell (refer to equation [4]), and can be expressed as:

$$total\_Lm = K \sum_{i=1}^{n} Lm_i$$

Where:

Total_Lm: LED lamp total luminous flux (lm)
Lm_i: luminous flux received by each solar cell
K is a correlation factor of total flux and partial flux

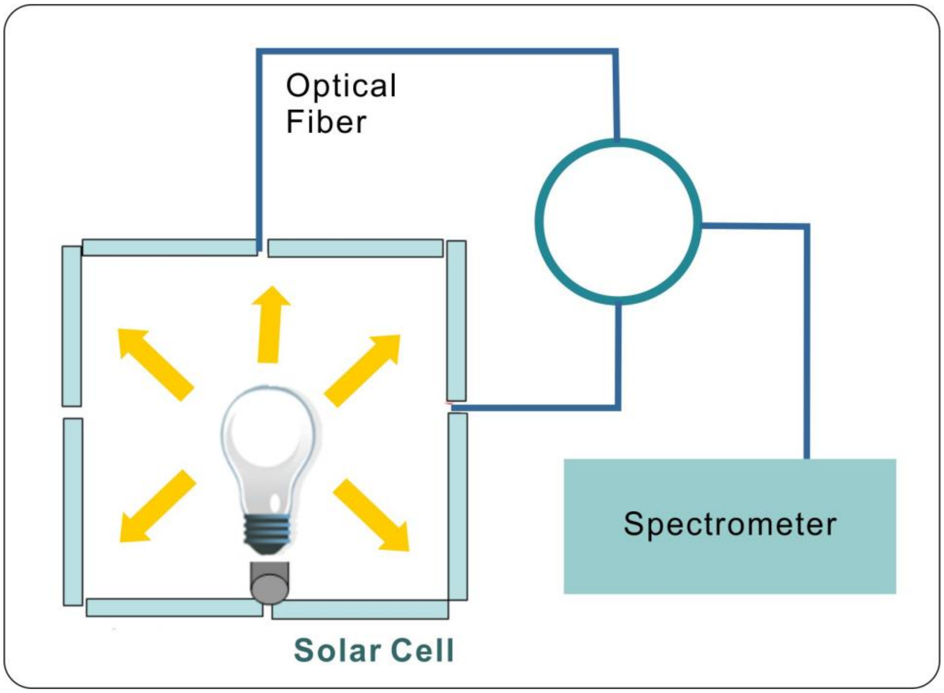


Figure 4: Implementation for an LED bulb

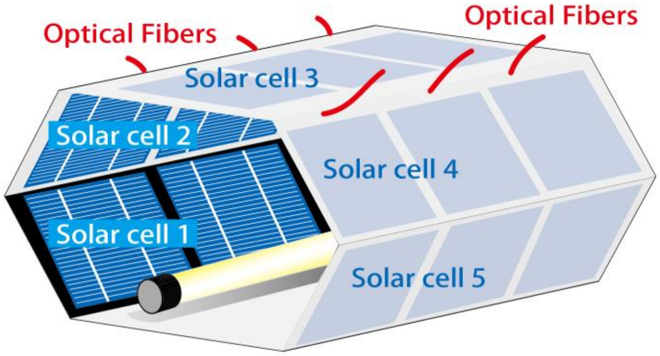


Figure 5: Implementation for an LED tube

System Setup

According to Energy Star program requirements for integral LED lamps, LED lamp manufacturers must offer electrical and optical parameters such as lumen, efficacy, power factor, correlated color temperature (CCT), and color rendering index (CRI) to consumers. The purpose of the system is to test all of these parameters in a production line, so that the LED lamp quality consistency can be assured. The system is equipped correspondingly to have the capability to measure LED lamp's total luminous flux, chromaticity, and electrical parameters.

The system includes an AC source, a power meter, a DC source, and an optical measurement unit. Take the system for a bulb as an example, the system is as Figure 6 illustrates. The optical measurement unit includes a PV module and a spectrometer with multi-optical fibers. The so called PV module is a square box and solar cells are placed on the inner surface planes. There are 4 solar cells placed on each surface of the square box. For chromaticity measurement ability, a spectrometer is used and multi-optical fibers are inserted between solar cells as shown in Figure 4. For other LED lamp form factors, like an LED tube, the system setup is similar, but the PV module is changed according to the form factor. Figure 5 illustrates the LED tube form factor.

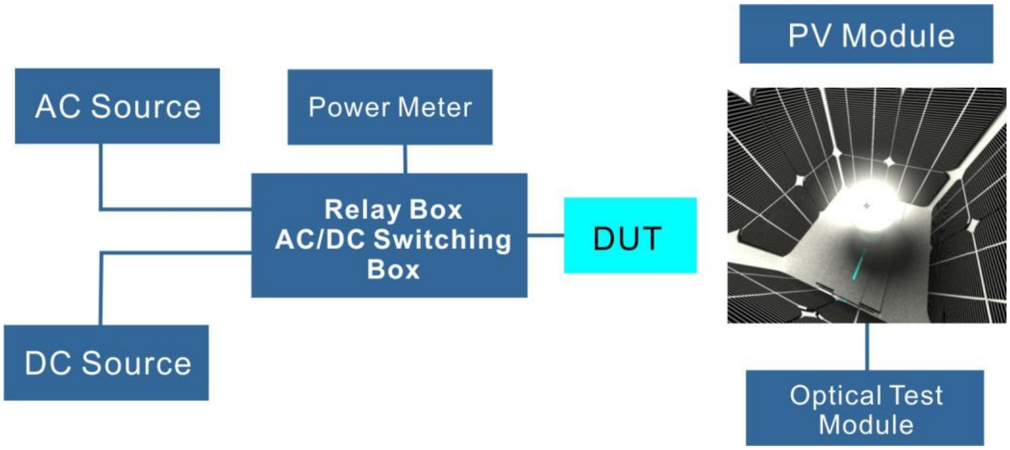


Figure 6: Test system architecture for LED bulb

Test Performance

The test performance of the system was evaluated for measurement repeatability and accuracy. The experiment results show that both the lumen and chromaticity repeatability of the system is good, and that the measured values correlated closely with the values acquired from an integrating sphere. Both the repeatability and accuracy experiments indicate that the test system is capable of performing production testing.

System repeatability

In order to test the repeatability of the system, a stable light source is required. A halogen lamp was used as the DUT, and it was seasoned for one hour. After a one hour burn-in, the halogen lamp was installed into the PV module and measurements were performed 400 times.

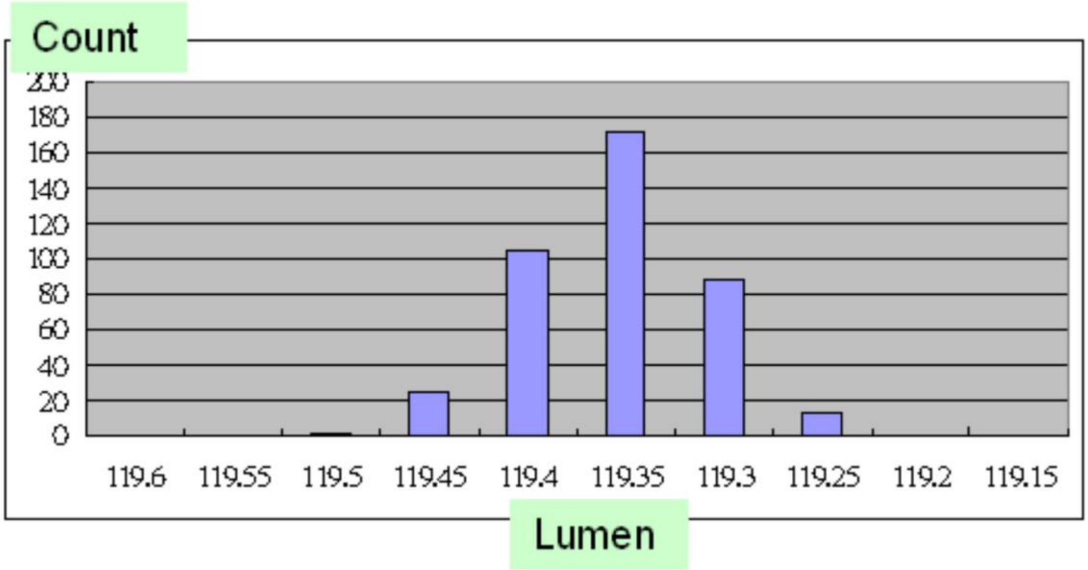


Figure 7: Repeatability histogram chart for luminous flux

Table 1 – System repeatability 400 times test result					
	Lumen	CCT	CRI	du'	dv'
Max.	119.5	2664	98.6	0.00019	0.00017
Min.	119.2	2659	98.4	-0.00019	-0.00018
Average	119.3	2661	98.498	0.00000	0.00000

- Luminous flux: (Max-Min)/Avg = 0.19%
- Max. Δu'v' = 0.00021

From Table 1, the luminous flux repeatability of the system is 0.19% and chromaticity CIEu'v' repeatability is 0.00021.

Accuracy experiment

The accuracy evaluation experiment measured an LED lamps value using the production purposed test system and also a laboratory standard integrating sphere, and then to compare the measured values. The benchmark integrating sphere system was a 50cm-integrating sphere with a spectroradiometer system. In total 20 LED lamps were tested (two types, 10 lamps of each type). Proper seasoning for the LED lamps was performed before the measurements, to insure that all of the lamps were tested when their light output was stable.

Experiment I: 7W warm white LED lamps

The DUTs used were 10 warm white A19 LED lamps, total luminous flux range was 350lm-430lm and CCT was between 2400K-2600K from the integrating sphere's measurements. The DUTs were burned-in for two hours before the measurements, and all of the measured values were recorded after the readings of the luminous flux were consecutively stable for 3 minutes, to assure that the test was performed in a steady state.

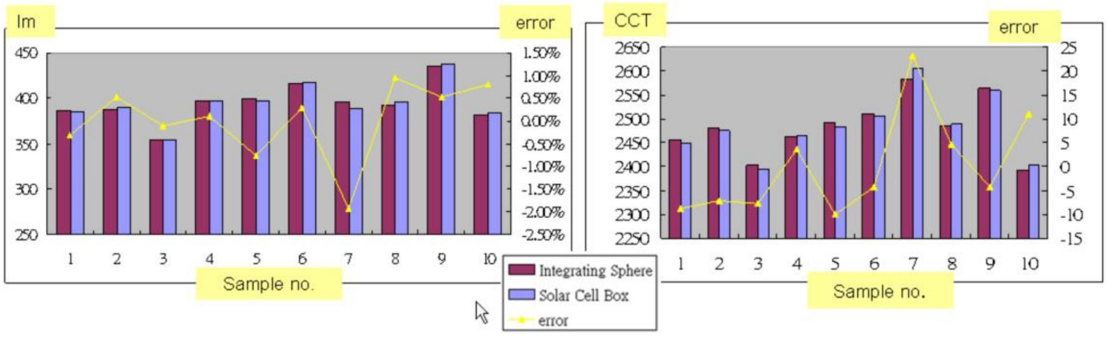


Figure 8: Measurement comparison from two systems (7W, warm white)

Table 2- Accuracy experiment summary I				
	Lumen	CIEx	CIEy	CCT
Max. error	0.95%	0.0023	0.0019	23.22
Min. error	-1.92%	-0.0030	-0.0016	-10.08
Avg. error	0.01%	0.0000	0.0000	0.00
Std.	0.85%	0.0015	0.0010	10.61

From Table 2, the maximum variation between these two systems of total luminous flux was less than 2%, and CCT variation was less than 25K. The standard deviations of total luminous flux and CCT were 0.85% and 11K respectively.

Experiment II: 10W cold white LED lamps

The DUTs used were 10 cold white A19 LED lamps, total luminous flux range was 500lm-570lm and CCT was between 5500K-5900K from the integrating sphere's measurements. The DUTs were burned-in for two hours before the measurements, and all of the measured values were recorded after the readings of the luminous flux were consecutively stable for 3 minutes, to assure that the test was performed in a steady state.

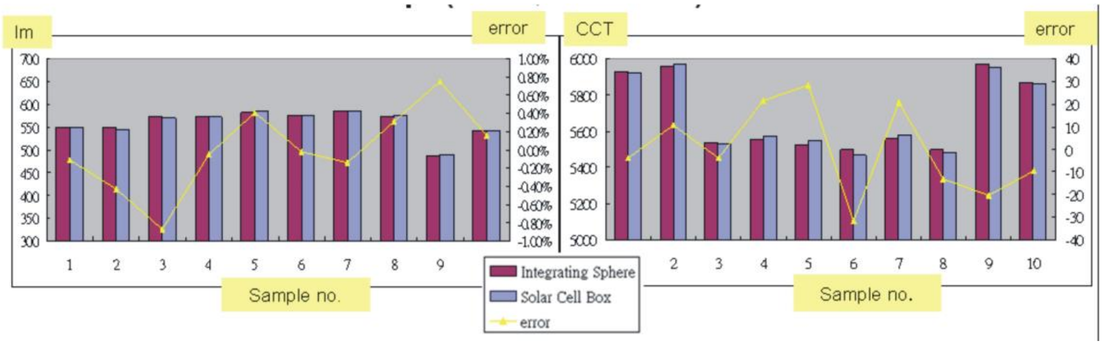


Figure 9: Measurement comparison from 2 systems (10W, cold white)

Table 3- Accuracy experiment summary II

	Lumen	CIEx	CIEy	CCT
Max. error	0.75%	0.0015	0.0011	28.37
Min. error	-0.87%	-0.0011	-0.0007	-31.44
Avg. error	0.00%	0.0000	0.0000	0.00
Std.	0.45%	0.0008	0.0006	19.72

In summary table 3, the maximum variation between these two systems for total luminous flux was less than 1%, and CCT variation was less than 32K. The standard deviations of total luminous flux and CCT were 0.45% and 19K respectively.

To summarize these experiments, the repeatability of the PV module method was excellent (lumen<±0.1%, Max. Δu'v' = 0.00021). The measured values from PV module were well correlated to the integrating sphere (lumen<±2%, CCT<±30). These values indicate that the PV module system is capable for use in production testing.

Other Measurement Considerations

Besides the electrical-optical parametric test, there are other considerations that need to be considered - specifically for LED lighting product measurements. Three of these are discussed in this section: cold test/hot test, flicker measurement, and optical spatial distribution.

Cold test/Hot test

In the above experiments, in order to get a stable LED light output, a proper pre-burn process was required. The LED light output is sensitive to temperature, or more precisely, the junction temperature of the LED chip. After turning on the LED lamp, the temperature generally goes up as time elapses, so the output light decays with time. If a test is performed immediately after the LED lamp is turned on, it is called a cold test, since the LED chip junction is still cold. If the test is performed when the light output is stable, it is called a hot test. Although the hot test value usually correlates to the cold test value, the light decay percentage is not same for each lamp, due to the variation in materials and production processes (see Figure 10).

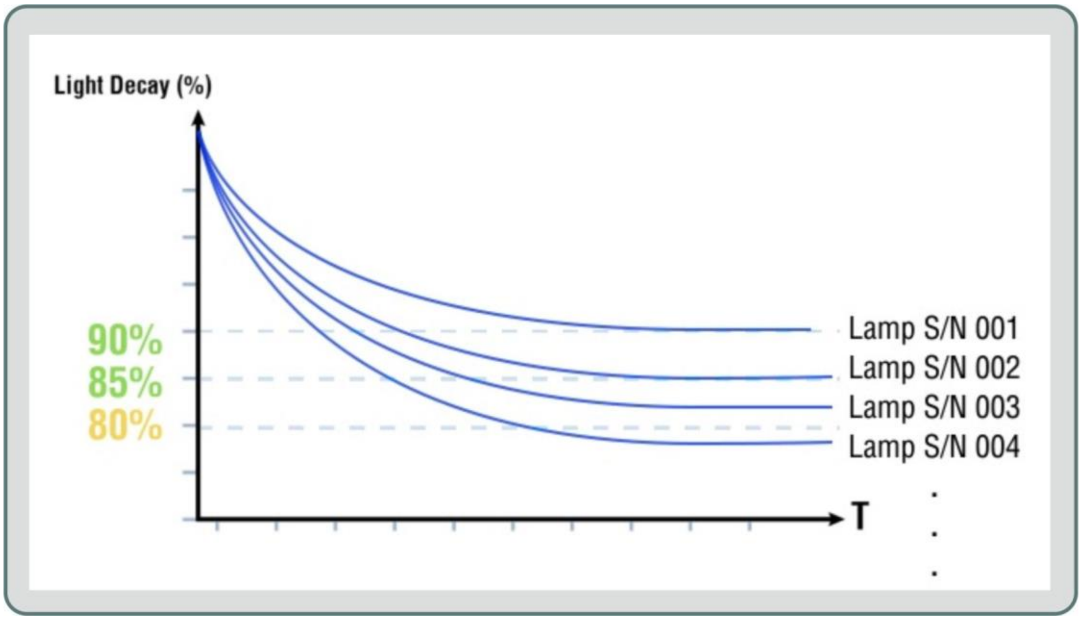


Figure 10: Light decay after LED lamp is turned on

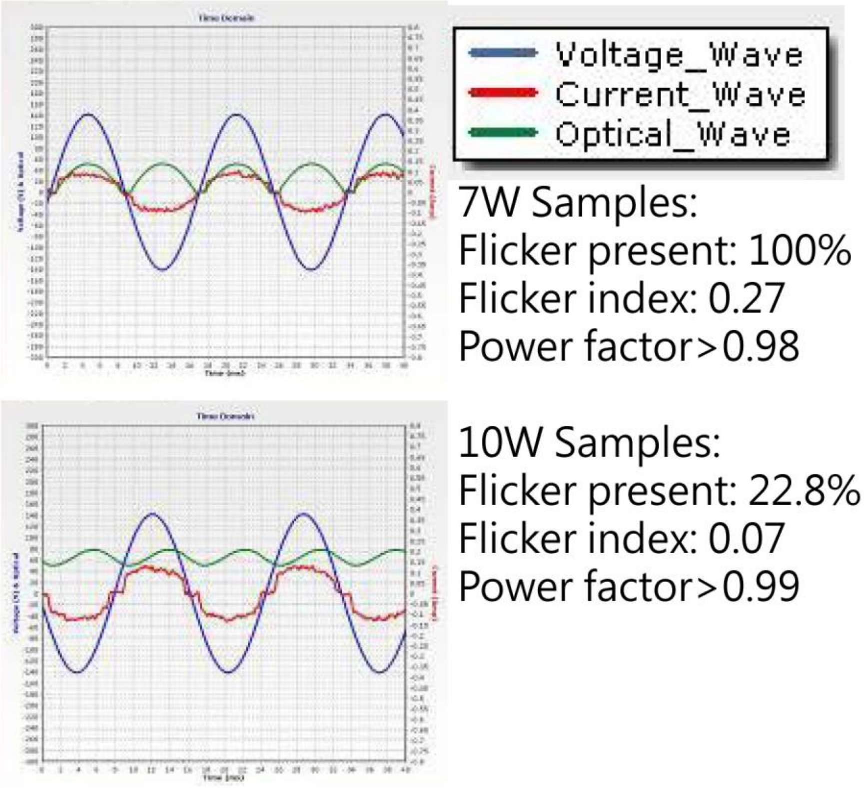
In LED lighting production processes, manufacturers usually perform a burn-in process in a big burn-in room. Some may argue that the pre-burn just before a test process is redundant. It is true if the test can be performed right after the burn-in process. However, in practice, the test is usually performed hours after this burn-in process, and the LED lamps have already cooled down. The purpose of the burn-in process is usually for reliability concerns, while the pre-burn before a test is for thermal equilibrium. Experiments show that with only a minute of turn-off before test, the light output goes up compared to the steady state value.

Flicker measurement

Flicker is also a concern for LED lighting products. For other traditional lighting technologies, the flicker phenomenon is almost the same for a given technology. However, in LED lighting, flicker may be very different from product to product, and this makes flicker measurement an important part of testing LED lighting. The major reason behind flicker is due to different driver designs.

ANSI/IES has defined two flicker indices: Percent Flicker and Flicker Index. Percent Flicker is based on light output amplitude variation, and Flicker Index is based on the variation of the light output energy. Other than light output amplitude and energy variation, the frequency of flicker is also important. Studies show that human eyes may perceive lower frequency, but still have some biological impact from invisible flicker. Generally, current regulations require that the flicker frequency, if any, must be higher than two times of the power line frequency, i.e. higher than the second harmonic.

The fast response time of mono-crystalline solar cell allows the PV module to sample the LED output optical waveform properly. Percent Flicker, Flicker Index, and frequency of flicker are calculated accordingly. In addition, the optical waveform is plotted with the voltage and current waveform to provide more useful information. Examples of these waveforms from two different LED lamp designs are illustrated in Figure 11.



7W Samples:
Flicker present: 100%
Flicker index: 0.27
Power factor>0.98

10W Samples:
Flicker present: 22.8%
Flicker index: 0.07
Power factor>0.99

Figure 11: Voltage, current, and optical waveforms in time domain for different LED lamp designs

Optical Spatial Distribution

As a relatively new technology for light sources used in general lighting, the optical spatial distribution of LED lamps is a concern. Generally speaking, LED light is a more directional light source, and the beam profile of the LED chip may vary from one chip design to another. In the early stages of LED lighting development, most of the product designs needed a large heat sink, and the beam angle was limited, even for non-directional purposes. When replacing an incandescent lamp with this kind of design, consumers certainly would not be satisfied. In the present, omnidirectional lamp designs are preferred, and some standards or government programs have a beam angle requirement. For example, the U.S Energy Star Program requests that the luminous flux between 135° to 185° must be higher than 5% of the total luminous flux for omnidirectional lamps (see Figure 12). Additionally, Japan JEL 801 also requests that at least 30% of the luminous flux must emit beyond 120° for LED tubes (see Figure 14).

The arrangement of the solar cells in a PV module is designed to meet the above spatial test requirement. The solar cells on the bottom surface of a bulb PV module (Figure 13) approximately represent the 135° to 185° zone. Similarly, the top three solar cells in the tube PV module may also represent the 120° zone of an LED tube (Figure 15).

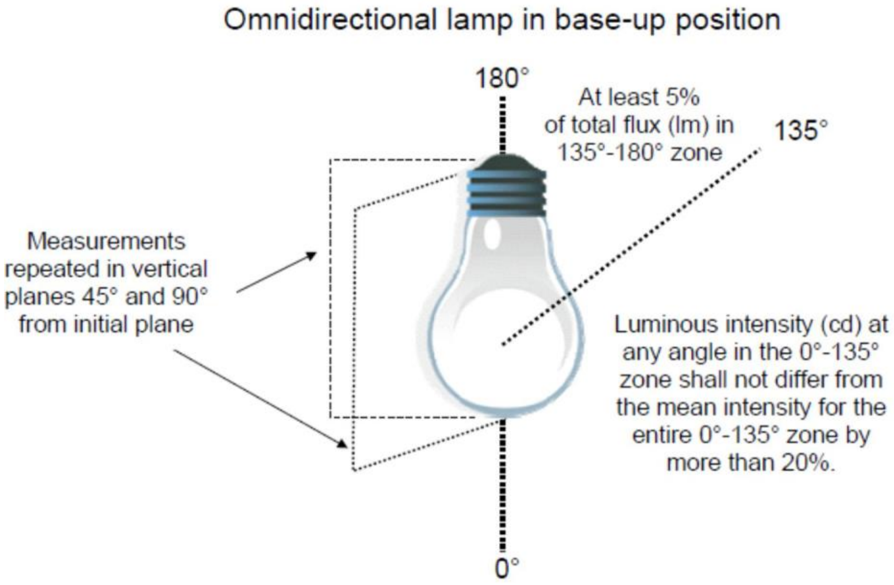


Figure 12: Energy Star request for omnidirectional lamp

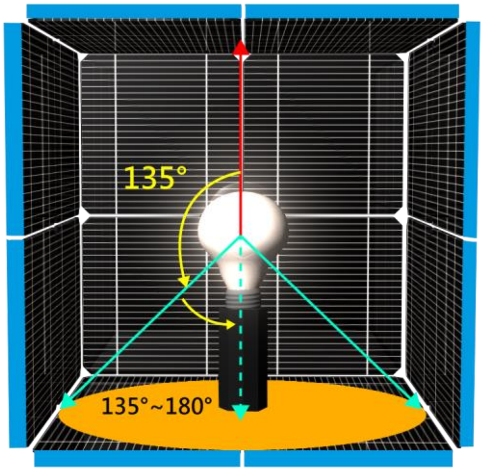


Figure 13: PV module for optical spatial distribution measurement (for bulb form factor)

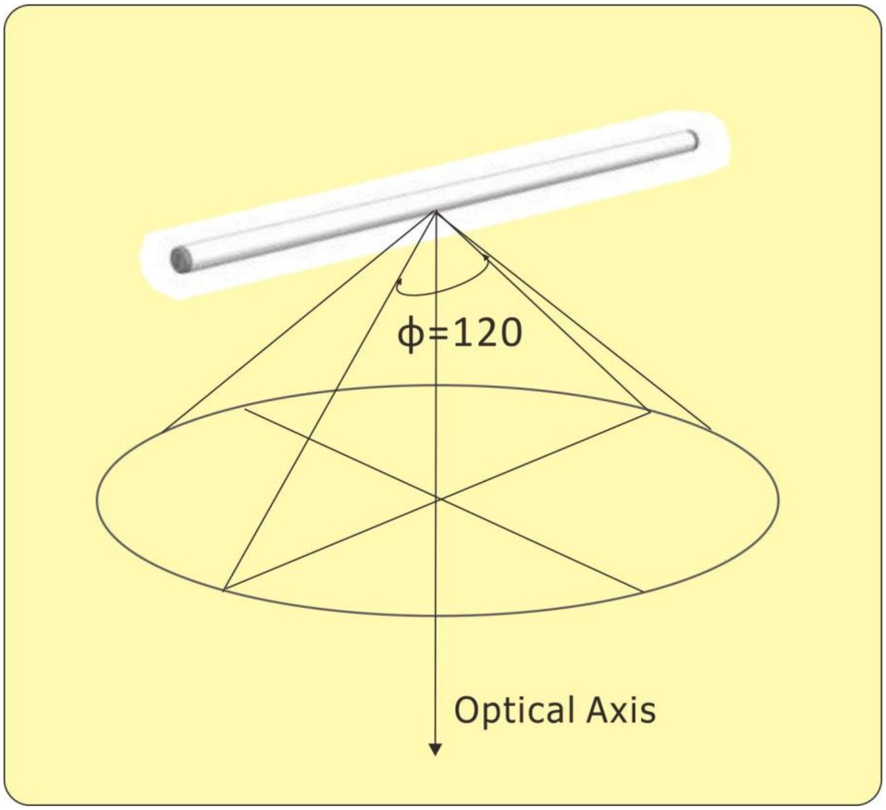


Figure 14: JEL 801 requests less than 70% of total luminous flux within 120° zone

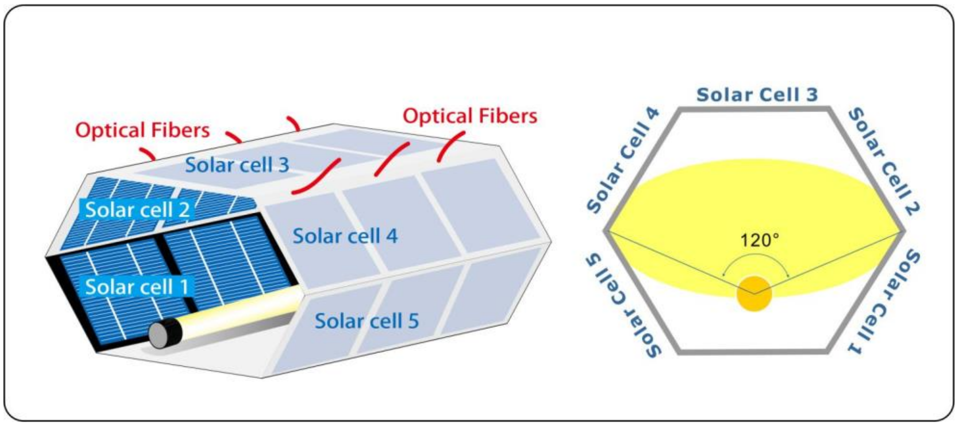


Figure 15: PV module for optical spatial distribution measurement (for tube form factor)

Combining With Automation Machines

The PV module test method features a compact tool size, high test speed, high cost effectiveness, and is also easier to combine with automation machines. An example implementation of the test method in an LED bulb fully automated production line is illustrated in Figure 16. The system is equipped with a pre-burn module in order to test in a thermal equilibrium state. The pre-burn time is DUT dependent; typically 40 to 50 minutes is enough to perform steady state testing.

The automatic line is a “tray-in/try-out” design. After loading the carrier tray, the pick & place robot picks an LED bulb to the pre-burn module. After pre-burn for the set time, the bulb is placed to the conveyor and transferred to the PV module for testing. The “off time” of the bulb from pre-burn module to conveyor is only a few seconds, so that the steady state can be retained. After the test, the DUT is sorted to either a pass or fail bin carrier tray, according to the test result.

Test items performed by the PV module include, but are not limited to, input power, power factor, total harmonic distortion, luminous flux, correlated color temperature, and color rendering index, as well as optical spatial distribution and flicker measurement.

Figure 16: Automatic production test line with pre-burn module

The Necessity of Production Testing for LED Lighting Products

There is an argument concerning the necessity of production testing for LED lighting products among LED lighting manufacturers. Some argue that production testing is not required for LED lighting products, because the LED chips have already been tested. Some may think that the consumers or end users may not notice quality issues. Some may be concerned about the test cost if applying the inconvenient standard measurement methods to the production line, especially when all of the manufacturers are suffering price pressures. All of these lead to a common phenomenon in the industry: only a few samples are tested for quality control.

Are these arguments valid? Is the quality of LED lighting products really as good as these manufacturers claim?

Two aspects can be considered in order to answer these questions: analyze the quality on the production line, and analyze the quality from the market. Here we provide facts from these two aspects: real production test data from an LED lighting manufacturer, and a market test report from the U.S government program.

Facts from real production test data

Real statistical production data from an LED tube manufacturer is provided in Figure 17. The nominal specifications are: 1100lm, CCT=6000K, CRI=70. Two batches of run data are provided, showing that there is a shift between the two runs. The data also shows that the span of the performance distribution is wide, even within the same run. Although the pass/fail criteria of this manufacturer are not strict, the fail rate is still noticeable. If such a wide performance distribution and such a high fail rate occur in the production line, the product quality definitely cannot be assured without 100% production testing.

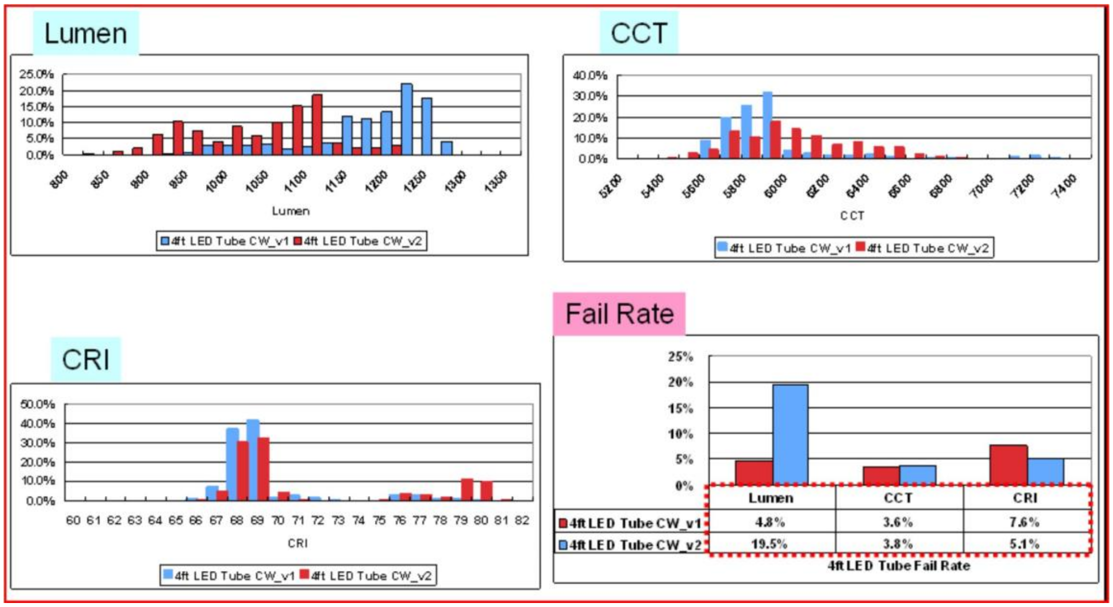


Figure 17: Real production test data from LED lighting manufacturer

Facts from U.S CALiPER program

The U.S Department of Energy (DOE) CALiPER program is one of the U.S DOE Solid State Lighting (SSL) programs. The program buys solid state lighting products from the market, and performs the photometric testing based on LM-79's standard testing methods. The purpose of the CALiPER program is to provide photometric data of the solid state lighting products which are available on the market, to have a glance at the technology trends, to provide a benchmarking baseline, and to check whether the performance is as good as the manufacturers claim.

The CALiPER program has been purchasing and testing general illumination solid-state lighting (SSL) products since 2006. In the latest CALiPER Application Summary Report 20, 38 different LED PAR38 lamps (named as Series 20) were tested. Evaluating how close the real performance is to the manufacturers' claims is an important part of CALiPER program. In this summary report, although most of the manufacturer claims for color related parameters were accurate, only 23 of these 38 samples met all three claims for input power, lumen output, and efficacy; as high as 40% of the samples failed to meet their claims for electrical/optical power related parameters.

LED Lighting Facts and Energy Star are also important programs of the U.S. government to build consumers' awareness and confidence in LED lighting products. Among these 38 Series 20 LED PAR38 lamps, 21 of them were listed by LED Lighting Facts, and 18 of them were Energy Star qualified products. Although these products were tested and measured under standard procedures before being certified or qualified, the test result from the CALiPER program still showed a significant fail rate in meeting the manufacturers' claims (refer to Table 4). The root cause of this phenomenon is unknown, however lamp-to-lamp variability is a possible factor suggested in the summary report.

From these facts from the CALiPER report, it implies that the current sampling tests in production is definitely not enough to make the products quality consistent. If there is not 100% production testing, there is a more than 40% chance that the products may fail to meet one or more of the claimed specifications.

Table 4: Fail rate of Lighting Facts listed and Energy Star qualified products in CALiPER Application Summary Report 20

	Lighting Facts listed Total samples: 21		Energy Star qualified Total samples: 18	
Items	Fail samples	Fail rate	Fail samples	Fail rate
Lumen output (lm)	7	33.3%	3	16.7%
Input power (w)	5	23.8%	1	5.6%
Efficacy (lm/w)	6	28.6%	4	22.2%

Conclusion

The accuracy and repeatable performance of the PV module test method has been proven, and the test method is also proven to fit production testing requirements. Evidence from both manufacturers and U.S. government programs indicate that the quality of current LED lighting products is not consistent, which certainly lowers consumers' confidence in LED lighting solutions. With 100% production testing coverage, quality can be assured, and LED lighting market adoption can be accelerated.

References

[1] IESNA LM-79-08. Electrical and Photometric Measurements of Solid-State Lighting Products

[2] JEL 801:2010, Straight Tube LED Lamp Standard

[3] Energy star Criteria version 1.4 Energy Star program requirements for integral LED lamps document

[4] IEEE Standard P1789, A Review of the Literature on Light Flicker: Ergonomics, Biological Attributes, Potential Health Effects, and Methods in Which Some LED Lighting May Introduce Flicker