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WHITE PAPER

The Next Big LED Testing Challenge: High Power LED Modules

Light emitting diodes (LEDs) have been around since the 1960s and were originally often used as indicator lamps and in seven-segment displays. An LED is essentially a semiconductor light source. When an LED is switched on (that is, is forward biased), electrons can recombine with electron holes within the LED, releasing photons and creating electroluminescence. The color of the light produced, which corresponds to the energy of the photon released, is determined by the semiconductor's energy gap. When compared with incandescent lights, LEDs offer several advantages, including lower energy consumption, longer lifetime, greater robustness, smaller size, and faster switching. In recent years, however, LED designs have evolved for new types of applications; today's high brightness light emitting diodes (HBLEDs) include automotive displays and exterior lights, backlighting for televisions and video monitors, street lights, outdoor signs, interior lighting, and an ever-expanding array of other lighting and display tasks.

But what exactly *are* HBLEDs? Typically, they are defined as LEDs that operate at 1W of power or higher, usually in the range of 1–3 watts. Although regular LEDs typically draw just 10–30 milliamps of current, HBLEDs generally run at 300 milliamps to 1 amp. Rather than being packaged in a 3mm or 5mm plastic dome with a pair of leads, HBLEDs are typically mounted on a small, thermally conductive board in order to draw heat away from the device's junction. The leads themselves must be thick enough to handle the higher currents associated with HBLEDs.

As bright as individual HBLEDs are, they're still not bright enough for many lighting applications. Multiple HBLEDs are often combined to create

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luminaires, such as in an LED light bulb for a retrofit application or a complete lighting fixture. This is a good solution when it's desirable to have the light fan out in multiple directions and where the luminaire's size provides sufficient space for multiple devices. However, in applications where space is very limited and/or the light must be directional, this approach is unworkable.

High power LED modules (HPLEDs) offer far more compact form factors than HBLEDs and can output lots of directional light. These characteristics have made them extremely popular for applications like automotive headlamps, projectors, and even some high power flashlights. HPLED modules consist of one or more large-die LEDs assembled into a single package and can handle higher currents than typical HBLEDs. It's common for a single die to be required to withstand currents of 10 amps or higher. These high currents produce a significant amount of heat, which must be dissipated and/or monitored during the characterization process. Modules are typically built on a heavy copper core board or other thermally conductive material in order to pull the heat out of the LED junctions. These heavy boards can be easily mated with a heat sink of appropriate size to keep the LEDs cool. Modules usually have a thermistor built in to the board to simplify monitoring the junction temperature of the LEDs. Despite manufacturers' efforts to dissipate the heat produced by the LEDs, operating junction temperatures for these modules commonly go as high as 140ºC.

How to test HPLED modules

As the popularity of HPLED modules has grown, new requirements for equipment to test them have begun to emerge:

- ***Greater power output*** — Today's HPLED modules are capable of DC power levels close to 100 watts and tomorrow's modules may require even more. Testing these modules properly at their rated operating points requires manufacturers to use test equipment capable of delivering this level of power.
- ***Pulse width modulation testing capability*** — Pulse width modulation (PWM) is a common technique for controlling the brightness of LEDs. In this method, the current through the LED is pulsed at a constant frequency with a constant pulse level while the width of the pulse is varied. By adjusting the pulse's width, the period during which the LED is in the ON state can be varied, thereby varying the perceived brightness. Although the LED is actually flashing, it's so quick that the human eye can't distinguish it from a constant light level.

Although the brightness of an LED technically could be dimmed by simply lowering the level of forward drive current used, PWM is a better option for a variety of reasons:

– *As the LED is dimmed, the PWM technique keeps the color of the light consistent.* The color of the light an LED emits is related to the forward voltage at which it operates. Although the forward voltage of an LED remains relatively constant as forward current is changed, it does vary, however, especially at lower current levels, where the forward voltage can change substantially. This slight variation in forward voltage would produce a slight variation in light color, which is undesirable in lighting applications. In contrast, with the PWM technique, the LED is pulsed using exactly the same current level for each pulse, so the forward voltage is the same and the color of the light emitted doesn't vary.

– *PWM provides a linear control over brightness.* The amount of light an LED emits is not linearly related to the amount of current used to drive it; in other words, reducing the drive current by 50% won't reduce the light output by 50% but instead by some other percentage. This non-linear property would make it difficult to apply a dimming scheme based on varying the current; each LED would have to have its light output vs. forward current characterized and the drive scheme calibrated to that curve. In contrast, PWM offers a much simpler approach to LED dimming; to make an LED output 50% as much light, simply reduce the pulse width by 50%. An LED that's ON for half as long produces half as much light.

– *PWM ensures greater power efficiency.* PWM employs a constant current level for each pulse, so the pulse level to use can be selected such that the LED is operating at its most efficient operating point, i.e., where the lumens produced per watt is the highest. That means the LED is operating at maximum efficiency no matter what dimming level is used. PWM, which is simple to implement and control with inexpensive digital circuitry, also offers the efficiency advantage that LEDs actually output more light for a given drive current when pulsed rather than at DC. Many LED manufacturers' datasheets include a graph of their products' forward current vs. luminous flux. If the manufacturer has taken the time to characterize the LED under both pulsed and DC drive currents, such graphs make it obvious that the pulsed characterization curve lies above the DC characterization curve. This is the result of the lower level of self-heating of the LED that pulsed current provides.

  Finally, the PWM method employs highly power-efficient switching circuitry. When the switch is turned off, virtually no current flows and no power is consumed. When the switch is turned on, nearly all the power is delivered to the LED. In contrast, in a variable current drive scheme, reducing power to the LED involves burning the excess power elsewhere in the circuit.

To emulate actual operating conditions, an LED should be tested under PWM by running a train of pulses through it and taking an integrated measurement of the light output over the course of many pulses using a spectrometer. During the pulse train, the forward voltage is measured on every pulse to monitor it for changes as the LED heats. Delivering this pulse train to the LED under test requires equipment capable of mimicking a PWM LED driver as much as possible, pulsing at frequencies as high as 10kHz with duty cycles of as high as 50%. It also must be capable of measuring the forward voltage at every pulse precisely, triggering a spectrometer to start the light measurement, and responding to the spectrometer's signal to stop.

- ***Test hardware with precise timing and capable of producing consistent pulse widths and shapes*** — To ensure the reliability and repeatability of the device efficiency calculations, the HPLED test equipment chosen must offer precise timing and consistent pulse shapes. An LED's efficiency is calculated by dividing the light power out of the LED by the electrical power into the LED. As a result, consistent pulse widths and shapes are crucial to obtaining consistent measurements of the light power out of the LED spectrometer by ensuring that the same amount of power is being applied to the LED with each pulse.

The latest generation of source-and-measure instrumentation has been engineered specifically to reflect the capabilities necessary to test HPLED modules. For example, Keithley's Model 2651A High Power System SourceMeter® instrument (***Figure 1***) provides 200 watts of DC power and up to 2000 watts of pulsed power output. Its PWM capability offers a programmable duty cycle from 0–100% in the standard DC operating areas and a duty cycle up to 35% at 50 amps and up to 50% at 30 amps in the pulse-only extended operating areas. It has precision timing and synchronization to 500ns to ensure high pulse width accuracy; its flexible digital I/O simplifies triggering other instrumentation included in the test system, such as a spectrometer. Finally, it has a 100 nanoamp range with 1 picoamp resolution, which makes it suitable for handling other types of electrical tests that HPLED modules typically require, such as reverse leakage testing.

Figure 1. Model 2651A High Power System SourceMeter® instrument.

Test system cabling concerns

As already detailed, characterizing HPLED modules demands the use of large currents and high power levels. As these levels rise, so too does the importance of proper test system cabling.

Source measurement unit (SMU) instruments, which are generally acknowledged as the best instrumentation option for LED testing, couple source and measure operations that would normally be done by two separate instruments into a single, simultaneous operation. SMUs allow test system integrators two cabling connection options between the instrument and the LED under test: two-wire and four-wire connections.

The cabling is simple in a two-wire configuration; the same leads used to source the current to the LED are used to measure (or sense) the voltage. However, this approach has a significant disadvantage; the leads through which the voltage is measured are carrying a large amount of current. Due to resistance in the leads, this large current creates a voltage drop across the leads between the instrument and the DUT. For example, if the test current applied to the LED is 20 amps and each test lead has 50 milliohms of resistance, the voltage drop across the test leads would be 1 volt per lead or a total of 2 volts. In two-wire mode, the voltage measurement isn't actually taken at the LED but instead at the point at which the test leads connect to the instrument, so the voltage measurement returned includes not only the forward voltage of the LED but also the voltage across the test leads. For this 20 amp test current example, that would produce a forward voltage measurement that's 2 volts higher than the true value.

Fortunately for LED test system integrators, SMUs are also designed to accommodate four-wire or Kelvin connections. In four-wire mode, a separate set of test leads (the sense leads) measure the forward voltage at the device. These leads provide input to the instrument's voltage measurement circuitry, which has very high impedance, so virtually zero current will flow. With no current flowing in these leads, there's no voltage drop across the leads, so the voltage measured across these leads is the same as the voltage across the LED.

Although four-wire mode can eliminate voltage drops in the test leads caused by high currents, excessive lead resistance can still cause measurement problems, including wasted power. Ohm's Law ($V = I \cdot R$) tells us that the voltage drop (V) is equal to the current level (I) multiplied by the resistance in the test leads (R). Therefore, a test current of 20 amps and test leads with 200 milliohms of resistance would produce a voltage drop of 4 volts. Power equals current multiplied by voltage ($P = I \cdot V$), so 20 amps multiplied by 4 volts means 80 watts of power that the test leads must dissipate as heat.

Another reason to minimize test lead resistance is that there's a limit to how large a voltage drop an SMU can compensate for. Unlike a DMM, in an SMU, the voltage sense leads are not just for making voltage measurements; they actually feed voltage back to the instrument so it can adjust its output based on this feedback. This voltage sense function is actually part of the SMU's source architecture rather than just a measurement circuit and SMUs have a limit to how much drop in the test leads they can handle. Exceeding this limit will cause the SMU to take incorrect readings and may have other adverse effects on the level being sourced. The size of the drop an SMU can handle varies from instrument to instrument so check the SMU manufacturer's datasheet for this specification and select wiring with resistance low enough to stay below this limit.

Finally, excessive lead resistance will actually slow the SMU down. Fast rise and settling times are desirable when pulsing an LED in order to obtain the narrowest pulse widths to minimize self-heating. Minimizing lead resistances makes faster rise times possible.

However, minimizing lead resistance isn't the only cabling challenge to take into consideration when working with large currents; minimizing inductance is equally important. Inductance is essentially a resistance to changes in current and results in voltage drops created across the test leads during the rising and falling edges of the pulse when the test current is changing (***Figure 2***). The magnitude of this voltage drop can be calculated by using the equation V = L * di/dt, where V is the voltage drop, L is the size of the inductance and di/dt is the change in current over time. That means any inductance in the test leads will cause an additional voltage drop during the rising and falling edges of the pulse but will have no effect at the top and bottom of the pulse, where the current is constant.

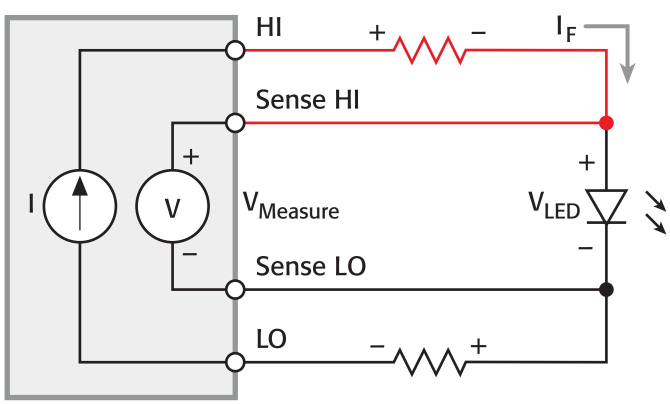

Figure 2. Effects of excessive lead inductance.

Although inductance will cause a voltage drop across the test leads during the rising and falling edges of a pulse, an SMU has the ability to compensate for this and will output additional voltage to drive through the drop; however, there is a limit to how much additional voltage it can output. Once this limit is reached, the rising edge of the pulse will slow to a level at which the inductance does not create a bigger voltage drop than the SMU can handle. Maintaining the speed of the pulses depends on minimizing the inductance of the cables.

Always check an SMU's datasheet for the specification on the maximum cable inductance the instrument can handle. Exceeding this limit can cause the SMU's output to become unstable and may damage the LED under test.

Cabling Considerations

Fortunately for test system integrators, minimizing the effects of excessive lead resistance and inductance is relatively uncomplicated. The simplest way to minimize lead resistance is to use the appropriate gauge of wire for the current levels involved; the greater the current, the thicker the wire that should be used. For example, when testing with 20 amps DC, 12-gauge or thicker wire is required. Another way to minimize lead resistance is to minimize contact resistance, that is, the resistance where two sections of the electrical path come together, such as where the test leads connect to the DUT. Minimizing contact resistance also requires keeping all contacts clean and secure. If solder is used, double-check the quality of all solder joints to prevent problems due to poor contact and high resistance. Finally, minimize the number of connection adapters and or cable extensions in the path between the instrument and the DUT. Each connector is another contact point that will typically add at least a few milliohms of resistance to the path, which could be eliminated by employing a longer cable rather than an extension.

Minimizing lead inductance is also surprisingly easy to accomplish; simply reduce the loop area between the high and low test leads by twisting the leads together into a twisted pair, separating them only where absolutely necessary. Coaxial cable is also better for this purpose than individual test leads. In a coaxial cable, the low lead is wrapped around the high lead with a thin insulating barrier between them, which minimizes the inductance. Coaxial cable is also easier to manage than a twisted pair of leads. The cabling for Keithley's Model 2651A High Power SourceMeter instrument takes these considerations into account. The coaxial cable supplied with the instrument is rated at just 3 milliohms/meter and 85 nanohenries/meter, ensuring the lowest possible lead resistance and inductance.

Conclusion

The testing challenges posed by HPLED modules, while significant, are far from insoluble. With the right instrumentation and an understanding of the appropriate connection techniques, manufacturers can develop automated systems that allow them to control their testing costs and remain competitive in the marketplace.

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