The UV-LED Paradigm Shift

By Paul Mills and Jim Raymont

On the game show *Jeopardy!*, the program turns the tables on contestants by presenting them with an answer and challenging them to come up with the right question. Sometimes it seems that the UV-LED market is engaged in its own version of *Jeopardy!* There are plenty of good answers—if we can only figure out what are the right questions.

With the game show, only the host starts the dialog with the answer. In the UV-LED world, there could be 25-plus UV-LED source/array integrators asking questions along with formulators, machine integrators and customers.

Some of the questions that seem important to guiding the discussion on proper LED measurement are:

- What are the wavelengths of the UV sources?
- What is their expected dynamic range?
- How fast should an instrument sample?
- Where is the right place to measure the LED?

From a measurement perspective, it feels like the clock has been turned back to the late 1980s or early 1990s. It feels as if we are answering many of the same questions for UV-LED users that we have answered for arc or microwave users. In the established world of mercury-based lamps these questions have long been settled and products have evolved based on broad industry consensus. You press a button and the instrument provides "a value." The user of the instrument still needs to understand what the value means and whether or not it is the "correct" value.

Care needs to be exercised when communicating. Differences between different brands of radiometers or instrument types with different features and responses can lead to different answers. Instruments have evolved over the years and their combination of electronics, optics and software are designed to provide solutions to the challenges of cosine response; the nature of the mercury spectrum; and the predictable effects of parabolic and elliptical reflectors.

If it seems as if mercury lamp suppliers and UV-LED manufacturers are sometimes speaking two different languages—that's because they are. The advent of UV-LEDs has resulted in a paradigm shift. This shift doesn't just require a new language, it also shatters some of the conventional wisdom and time-honored approaches to UV measurement. Developing a new prescription for how to measure LEDs has been made more difficult by the moving target nature of a solid-state technology that continues to morph and obsolete itself at a rapid pace.

The goal of this article is to suggest a number of important, but as yet unresolved questions that are fundamental to measuring UV-LED performance. The answers to these questions will determine if current measurement solutions will work; need to be modified; or if a new class of UV-measurement devices will best address the needs of its users.

What is the Spectral Output of a UV-LED Light Source?

Any device that measures a source of irradiation—whether it's visible light, Infrared (IR) or ultraviolet—requires a sensor that is sensitive to that portion of the spectrum under test. These detectors must accurately convert small changes in the incoming energy into corresponding changes in electrical energy while discriminating against wavelengths outside the band of interest.

For example, suppose that you are a camera buff who wants to accurately measure light so you can take proper photos. Your goal is to design a very accurate and sensitive photographic light meter. Since you might photograph under a range of different light sources (i.e., tungsten, fluorescent, sodium vapor, sunlight and candlelight), you need an instrument that measures across a wide band of light sources.

The sources generally emit light in a range of about 380 nanometers (violet) up to about 740 nanometers (red). In designing your light meter, you come across a light sensor that uses a popular photodiode. It's affordable, the right size and the manufacturer provides a chart that shows its optical characteristics. Figure 1 is, in fact, a fairly representative optical response for many popular photoelectric diodes. Note that the detector's response curve is pretty close to linear in the visible portion of the spectrum (see inset). Though the response curve is not "flat" in the 380-740 nm band, it's known and predictable. Through some clever engineering and using a combination of mechanical (optical) components and electronic circuitry, you can build a light meter that provides you with reliable measurements.

Suppose one day you decide that you want to start doing IR photography instead. This involves working with sources in the 750-950 nm IR range. There's a problem with your old light meter. Measuring 900 nm with a detector, filters and circuitry engineered for visible light causes

FIGURE 1

Optical response of a typical photodiode sensor

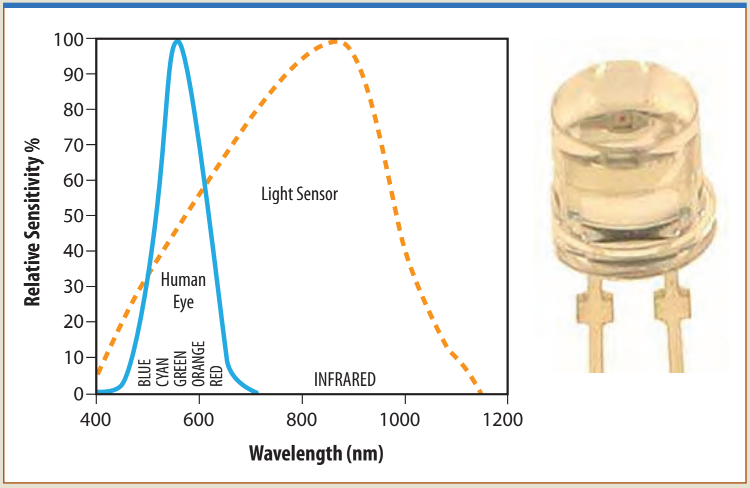


FIGURE 2

Typical bandpass filters used across the UV spectrum

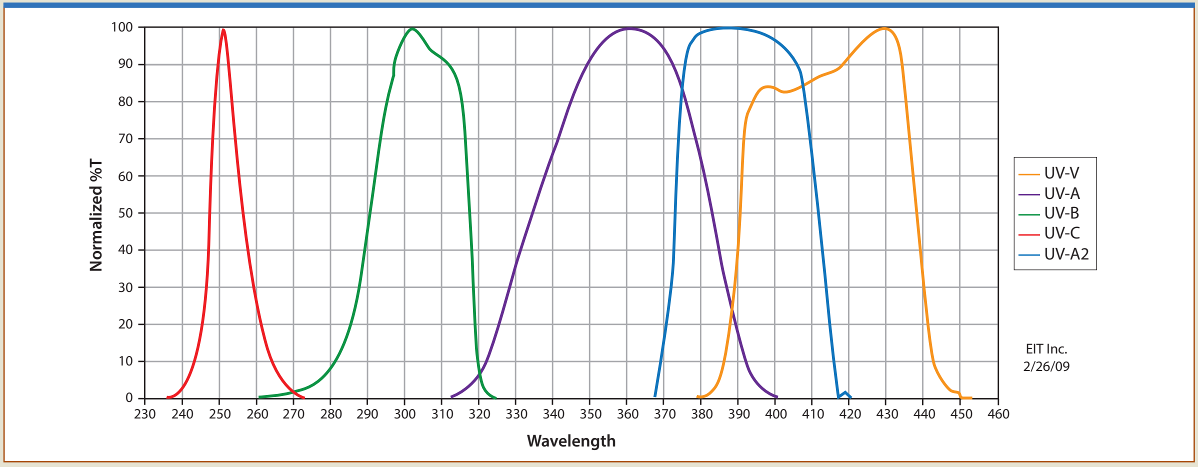
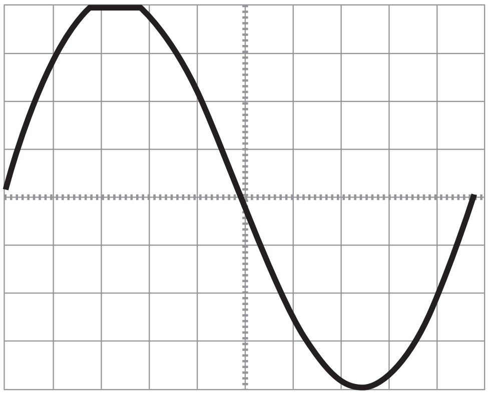


FIGURE 3

Example of signal clipping



some measurement problems when used with infrared. It produces a reading, but the reading is likely to be misleading since the instrument is intended for a different range of light sources.

That's the UV measurement problem with LEDs. The existing instruments were designed for light sources that are in a different spectral region. They produce a reading, but the reading can be misleading when used with new LED light sources. The chart in Figure 2 shows the bandwidth configurations developed over many years for arc and microwave-type lamps. You can see that a 395 nm LED would fall to the high side of the UV-A band and the lower edge of the UV-V band.

The solution has been to engineer a device optimized for 395 nm and the answer was a new combination of optics, detector and circuitry dubbed UV-A2. The chart in Figure 2 illustrates how the UV-A2 band satisfies the need for a better (more linear) response in the long wavelength LED market.

But there is still much uncertainty about what wavelength for the LEDs will emerge from the chip manufacturers; whether a new bandwidth will be required; or which broad range detector will emerge as the best solution.

What is the Anticipated Power Output of a UV-LED?

The minimum and maximum expected amplitude of an incoming signal is an important determinant for designing a measuring device. It must be sensitive enough to measure the weakest signal and of sufficient dynamic range to accommodate the strongest signal. UV-LED output has increased steadily from only a couple of hundred milliwatts per square centimeter a few years ago to more than 10W per square centimeter today (and twice that much in the current development labs). This poses a problem for existing radiometers.

Most conventional radiometers were intended to measure light sources up to about 10W per square centimeter. Though most users mistakenly regard LEDs as less powerful sources than arc or microwave lamps, their intensity in a narrow-band region is very potent. The latest generation of LEDs challenges the dynamic range of existing instruments. You may be familiar with clipping in audio applications where loud peaks are artificially attenuated by amplifiers. The result of trying to measure with a device that has inadequate dynamic range is "clipping" that results from overpowering the device. Clipping produces a lower irradiance measurement than the LED may be generating. See Figure 3.

To design a proper UV-measurement instrument, engineers need to anticipate the appropriate dynamic range of the source. In a market environment where the light source output power doubles every couple of years, this is an engineering challenge.

FIGURE 4

Cosine effect on UV irradiance

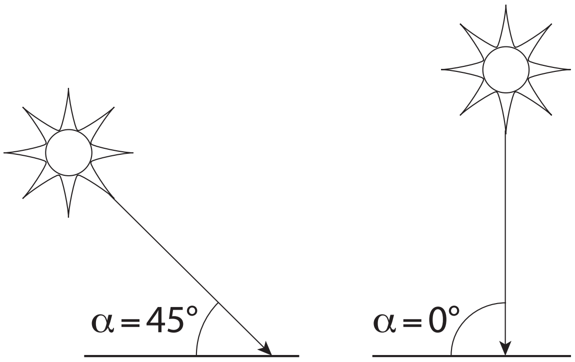
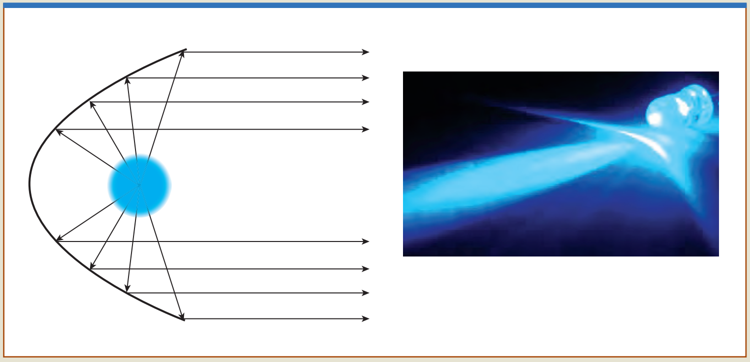


FIGURE 5

The optical footprint: traditional lamp vs. LED



Still, it's important to not become so caught up in the numbers that we miss what's really important—which is how the chemistry reacts. As long as there is adequate irradiance and energy density to fully cure the material in the process time desired, anything else is really just excess energy.

Where do you Measure an LED?

If the UV light that emanates from a source were uniform everywhere, it would be much simpler to measure—but this is not the case. UV intensity falls off the farther distance it is away from the light source. In fact, the fundamental principle is that "if a point source radiates light uniformly in all directions through a nonabsorptive medium, then the irradiance decreases in proportion to the square of the distance from the object." But that is a big "if" since real-world UV-LEDs are neither point sources nor do they operate in a nonabsorptive medium.

Traditional UV lamps are not always single-point sources either. UV light from a lamp strikes the radiometer's detector from many angles as shown in the Figure 4 diagram. Light from directly above the radiometer produces a different reading than light coming from a slight angle. This causes an error referred to as cosine error. In order to properly measure the light coming from various angles, the instrument must correct for the effect of the angle between the detector and light source.

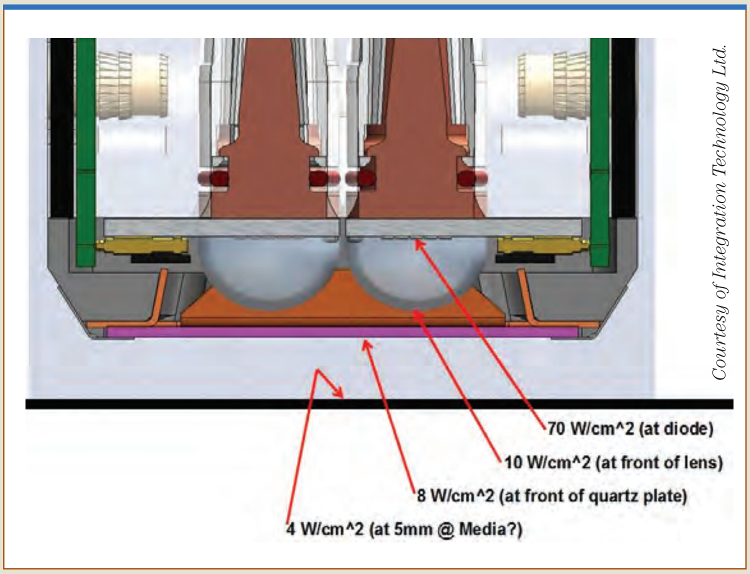
The angular cosine correction is achieved by tinkering with the response of the detector and optical components such as a diffuser. A perfect detector and diffuser combination has an angular cosine correction of unity, regardless of the angle of incidence. For existing instruments, the optical components are designed to achieve or replicate a cosine response in the instrument. This response is not always able to distinguish tightly packed UV-LEDs.

A second complication in the geometry of measurement is that those tiny LEDs do not radiate light uniformly in all directions, especially compared to traditional lamps with reflectors (Figure 5). The optical characteristics of current LED sources make it more challenging to decide where to best measure their UV output.

Recently, the LED lamp manufacturers have begun to develop optical components that can alter the output of their arrays again, sometimes with the goal of producing a higher irradiance specification. When comparing manufacturer specifications, be aware that there is no agreement, let alone industry standards, for reporting UV-LED measurements. As the illustration in Figure 6 shows, this can make it difficult to compare the

FIGURE 6

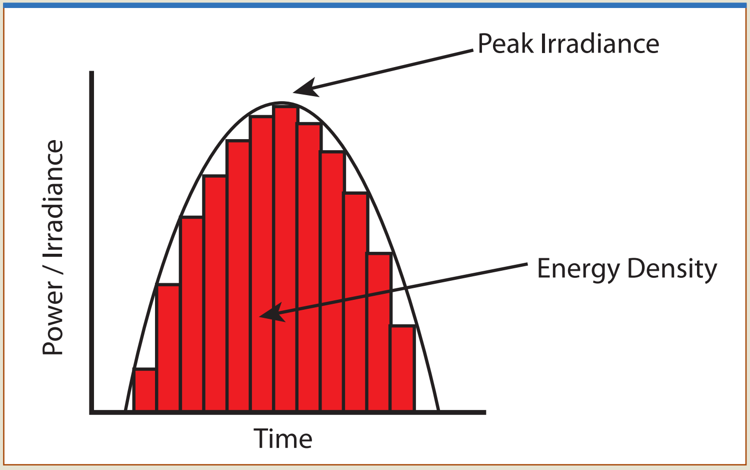
The "Where Do I Measure?" dilemma



Courtesy of Integration Technology Ltd.

FIGURE 7

Computing energy density (joules)



manufacturer's specifications without knowing much more about how the measurement was taken. Measurements made even a couple of centimeters apart can be dramatically different.

It's likely that the question of where to measure—such as always "at the glass"—can be answered without difficulty. But if various manufacturers continue to develop LED sources which focus their power further out from the LED array, they may be understandably reluctant to accept this method since these arrays will be intentionally designed to provide even greater irradiance at another, somewhat further distance. The question of where to make a standardized measurement of LEDs may, therefore, remain understandably unresolved as competing ideas about their optical characteristics are sorted out.

How do Sampling Rates Affect Irradiance and Energy Density Calculations?

For thermal processes such as curing paints and baking cookies, two key parameters are vital—temperature and time. Proper results depend on both measures. Successful UV curing relies on two similar measures—irradiance (a measure of UV intensity) and time. Without sufficient time, UV curing may be incomplete and the result compromised. In fact, the combination of irradiance and time is so important that a measure known as energy density (sometimes referred to as "dose") is almost always provided when specifying a UV-cure process.

(Note: It is important to stress that an energy-density value by itself is not enough to properly define a cure specification. From a UV-source standpoint, the irradiance value; type of spectral output; and the absence/presence of infrared all contribute to the cure process for a specific application. Parameters such as the coating thickness also need to be specified.)

In a mathematical sense, energy density can be thought of as the area under a curve that measures irradiance over time. See Figure 7.

You might remember from math class that finding the area under a curve is called integration, and that one technique to find this area is to break the area up into narrow rectangles and then add them all together. Obviously, the narrower the rectangles, the more precisely the area can be measured without missing the peak irradiance value. This is how many radiometers (originally dubbed "integrating radiometers") measure energy density.

The instrument takes many irradiance (sample) measurements every second, and then adds the values together. The push has been to faster and faster sampling rates in order to achieve high resolution and accurate irradiance calculations that can lead to more consistent energy-density calculations. The more samples that are taken over time, the "narrower the rectangles," so to speak. Today's radiometers sample hundreds (even thousands) of times per second.

But what happens when you are trying to measure something that's also changing at the same time? Some LED electronic control systems use a scheme called Pulse Width Modulation (PWM). With PWM, the supply voltage is turned on and off rapidly to alter the output of the light source as illustrated in Figure 8. The strobing of the LED is normally so rapid that it's invisible to the eye and, for many curing processes, it works perfectly well.

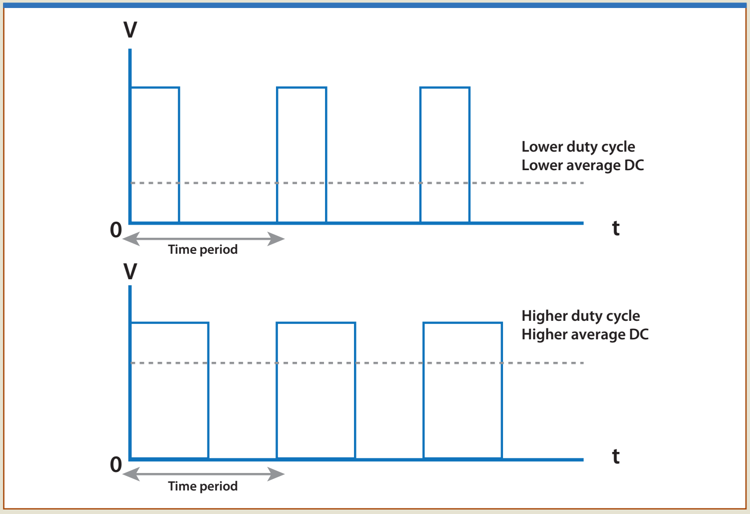
While PWM may allow the manufacturer to vary the output power of the array, turning the light source off and on very rapidly can create a challenge when taking samples at the same time. It can be like trying to take photos of a spinning fan blade—it's hit-or-miss. The sample energy-density readings may not accurately reflect the true measure and, depending on the algorithm used to used to calculate the irradiance and energy density, it may be higher or lower than the true values.

What are the Right Questions?

The preceding questions address important technical matters. The

FIGURE 8

Pulse width modulated signal



answers affect the design of radiometers intended for measuring UV-LED performance. But they do not address all of the unresolved issues. Many of the existing UV instruments were designed with popular applications in mind. The versatile Power Puck®, for instance, is well-suited for use on industrial conveyorized systems. But the Palm Probe® was designed to reach into recesses and areas where a Power Puck will not physically fit.

What are the likely uses for LED and how does the packaging of the test instrument need to be adapted? Perhaps LEDs will someday replace conventional lamps in applications where an LED analog of existing measurement tools will fit the bill. But LEDs also open up new applications, such as digital printing, where a different size or shape may be useful.

At this time, there are more than 25 manufacturers of commercial UV-LED sources targeting industrial UV applications that we are aware of (and probably a number that we are not). The industry is nascent and changes significantly from year to year, making it challenging to design a measuring device for equipment that moves from undefined to obsolete within a short time span.

UV-LEDs have opened up new markets to UV curing, in addition to being a possible solution for existing UV applications. Many people have the opportunity to use UV sources for the first time and do not have the experience that many of us have gained over the years with spot, arc or microwave UV sources. We need to:

- Welcome them to our industry
- Continue to offer educational opportunities
- Honestly present the advantages and disadvantages of UV-LEDs
- Target applications that are best suited for UV-LEDs

With years of proven performance and expertise at measuring UV, there is no shortage of solutions and good answers. The problem is agreeing on the right questions. ◗

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