Recent Advances in Measuring UV LED Arrays

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UV LED sources and the applications in which they are used are changing and expanding. As applications for UV LEDs move from lower hanging fruit to more challenging applications, the technical demands and rigors of process measurement are expected to increase. This paper looks at trends in LED sources and the recent advances made to measure them more accurately and reliably.

1. The Status of UV LEDs and Expected Future Trends

The level of penetration of UV LEDs into a particular market appears to vary greatly depending on the market and application. For example, LEDs are well-established in the spot cure adhesive and digital inkjet markets while the penetration, adoption and transition to LEDs has been considerably slower in other traditional UV markets such as that for wood coatings or medical devices.

A number of factors might impact the observed LED adoption rate, including:

- Size of the cure area. UV LEDs have grown fastest for application with relatively small footprints. This might be due to the fact that cost of the LED diodes themselves had generally made UV LEDs more costly for large arrays than arc or even microwave lamps.

- Maturity and condition of existing UV sources. In some markets, equipment is becoming more obsolete and the business case for converting to LED is clearer. In those industries where turnover is more frequent, conversion to LED has been more rapid.

- Availability of suitable chemistry that meets performance requirements. The conversion to LED appears to be more rapid where some of technical barriers are less formidable. For example, coatings which required harder, more durable surface properties have been more challenging for LED since the arrays do not have the short-wavelengths helpful in creating harder surfaces. Thus UV LEDs have found less resistance in applications such as adhesives, sealants, conformal coatings, where such surface properties are not required.

- Expected transition costs including qualification and documentation if required. Requalifying processes with a new technology can be costly and time consuming and this provide a hurdle for replacing incumbent technologies.

Adopting UV LEDs is easier in markets that offer a proven, (well-integrated, or packaged) turnkey solution with coordinated vertical integration. For instance, the ability to purchase a UV cured adhesive that is matched and packaged to an UV LED source from a single vendor speeds the development and boosts confidence in users who are considering the transition to LEDs. The same is true for digital print/press manufacturers who sell UV LED cured inks and sources as part of a one-stop transition strategy. Markets in which there is close (even in-house)

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coordination of the UV curing process have inspired the most confidence in manufacturers to deploy the technology.

This last point highlights the importance of consistent communication and the need for a common language and protocols in describing the UV LED curing process. Some of the early claims by equipment and chemistry suppliers relied on faulty assumptions, and inconsistent practices and procedures for specifying or measuring UV cure processes. As the smoke has cleared, a clearer picture of how these new sources differ from conventional technology and a more rigorous understanding of the changes needed to measure them has emerged as UV suppliers have become more knowledgeable.

UV LED technology continues to advance. The irradiance of LEDs continues to climb, due to more efficient chips, more sophisticated power supply technology, better cooling, and high-tech optics). At the same time, the value of LEDs continue to improve as LED costs decline due to greater scale, increased competition and advances in LED-compatible chemistry. The boundaries of LEDs continue to be pushed with respect to shorter wavelengths and higher irradiance levels. LED suppliers have commercialized LED arrays that combine diodes of multiple wavelength (such as 395nm and 365nm diodes in a single array). Such mixed wavelength sources offer process benefits (and potential challenges to process measurement).

Both Winston Churchill (and Uncle Ben in Spiderman) have cautioned that “With great power comes great responsibility.” So it is with UV LEDs, since high power LED sources provide manufacturers with greater freedom and offer the ability to run systems at higher production speeds that may offer economic benefits, reduce the applied power to drive the LED array to extend its useful life, or to locate the source further from the part surface.

However, to those involved in UV curing in the early 1980’s the discussion of higher power sources might feel like “déjà vu all over again.” Similar discussions were common when the electrical power applied to UV arc lamps increased from 200 Watts per inch (WPI) to 300 WPI to 400 WPI and more. Some might ask: “So Watt? Isn’t more power always better?” But history reminds us that “using a bigger hammer” can have unintended, (an unwanted) outcomes. End users need to be responsible and understand how their coatings, inks, and adhesives will react to different irradiance (W/cm^2) and energy density (J/cm^2) levels, along the added heat produced at higher LED power output levels.

These improvements to LED sources and compatible formulations have opened the door for converting applications such as wood coatings, medical devices and wide web applications currently using conventional mercury-based lamps. However, these applications may have more stringent process windows, or be more prone to defects or failures if the curing process is not well defined or maintained.

When considering how to measure the LED processes, we have noticed two common misunderstandings. First, some question why, measure their LEDs at all, since LEDs are reputed to have extremely stable output over a long lifetime. In the “real-world” we find that not only do LEDs fail unexpectedly, but a wide range of other factors affect the output of an LED diode.

A radiometer designed for UV LEDs will let you know if:

- The UV output has changed due to factors such as contamination to the quartz window of the source.

- Power supply levels or setting have changed
- Cooling efficiently (water chillers are not working properly or fans are blocked)
- Process speed has changed
- The distance from the LED to the substrate has changed
- A different wavelength LED was mistakenly substituted

A second misnomer is that using an existing radiometer designed for conventional UV sources can accurately and reliably measure UV LED sources. The remainder of this paper addresses this important issue, since many of our customers have found that using the wrong instrument to measure their UV LED arrays has led to cure problems, downtime, rejects and returns.

LED radiometers are critical and fundamental tools for enabling consistent, clear communication both within a company and between its suppliers. They are used to establish the needed process window, and to transfer the process to the production floor. Radiometers are used within a single facility on single or multiple production lines and to make sure that lines in different locations are producing products the same way.

2. Recent Advances in UV LED Measurement

Existing UV measurement systems can be made to work acceptably well with conventional broadband mercury based UV sources. Measurement of UV energy from a medium pressure "broadband" mercury source depends on measuring the amplitude of the peak wavelengths within the band of interest since the energy between the peak wavelengths is weak relative to the energy of these peaks.

Certain spectral intervals or "bands" of output in mercury based lamps have been designated as UVA, UVB, UVC, and UVV. ("UVV" in this paper denotes wavelengths in UV-Visible transition range and not short wavelength "vacuum" UV). There are minor variations in the definitions of designated UV bands but they generally fall into the ranges identified in Table 1.

Table 1. Broadband (Mercury) UV Band Designation

Band Name Identifier	**Wavelength Range**
UVA	315-400 nm
UVB	280-315 nm
UVC	200-280 nm
UVV	400-450 nm

Different lamp types (Hg (H), Hg-Fe (D), and Hg-Ga (V)) emit different signature wavelengths. These wavelengths and the associated energy in each of them, when matched to formulations, are used to achieve different properties in the cured end product. The energy in the shorter UVC band, tends to provide greater surface cure properties and can be used to achieve desired surface properties such as stain resistance, scratch resistance, and proper gloss, matte, and friction. The energy in the longer UVV band penetrates more deeply in the polymer and is better suited to dense, opaque, or thick formulations.

The spectral output of UV LED sources are much different than conventional mercury light sources. The central wavelength (C_p) is the wavelength which contains the highest amplitude line and is generally used to denote the midpoint of the spectral distribution of the LED array.

Commercial UV LED systems are typically described by the central wavelength, C_p, within a given band. For example, a curing system described as a "395" means that a typical LED in the assembly has C_p of 395 nanometers (nm).

EIT has developed bands for UV LEDs and has identified them as “L” band designations tied to nominal central wavelengths as shown in Table 2 below.

Table 2. EIT UV LED L-band designations

Band Name Identifier	**C_p Wavelength Range**
L 405	400-410 nm
L 395	390-400 nm
L 385	380-390 nm
L 365	360-370 nm

The “L” is intended to denote an instrument situated for an LED type light source, while the numeric portion denotes the ideal nominal central wavelength of the source in nanometers (nm).

3. Description of Current UV LED Sources

Currently available UV LED sources produce UV in a range with a distribution of +/- 45-55 nm wide.

Photopolymer formulations vary in their efficiency or ability to be cured by different wavelengths. More efficient curing can be obtained if the UV energy used for curing is concentrated in the optimal band. Lab testing along with information from formulators will allow users to select an LED source with the most efficient UV output for their process.

Accurate absolute measurements of LED UV energy are more difficult to obtain for central wavelength band ranges much greater than about 10nm. Good process control requires accurate UV energy measurements and restricting bandwidth provides more accurate measurement.

The buyer of an LED source needs to know the output wavelengths and intensity of the device they are evaluating and/or purchasing. Restricting the acceptable C_p wavelength range to 10 nanometers makes such information easier to obtain.

Proper characterization of sources provides assurance to end users that the manufacturer did not use longer wavelength LEDs because of their generally lower price and higher energy output.

For a 395 nm source, we have found that 98% of the power is concentrated and emitted in the range between 377nm to 422nm. The output is many times the width of an individual mercury spectral line. The output for a typical 395 nm source is show in Figure 1 below.

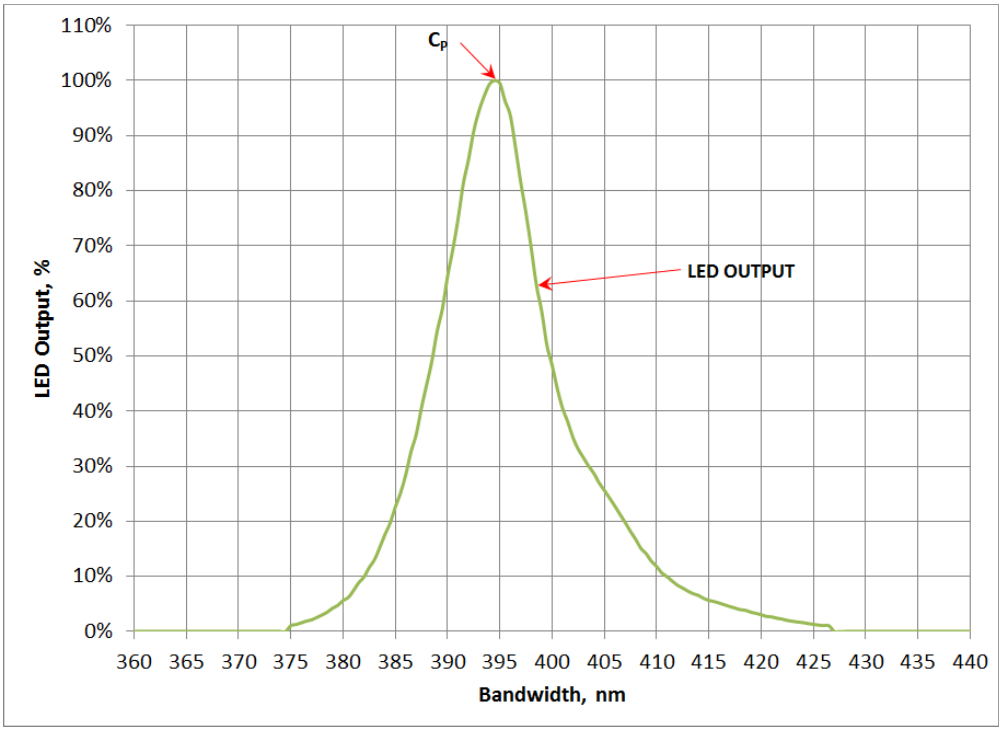


Figure 1. Typical UV LED 395 nm Spectral Output (Courtesy EIT LLC)

Commercial UV LED curing systems are comprised of individual diodes mounted in an array that can vary in shape. Source manufacturers use proprietary methods to select or “bin” the individual “diodes” from those commercially available. There are also tradeoffs in the selection or binning process for wavelength, output intensity and voltage needed to drive the device. Tighter device binning can improve the homogeneity of the source but the tradeoff is higher cost.

The C_p of any LED in the assembly can typically vary by ± 5 nm. The amount of permissible variation in spectral output acceptable to an individual manufacturer assembling commercial UV LED curing system has important consequences.

It is common practice for most LED assembly manufacturers to specify LED curing systems in this manner. That is, while the manufacturer specifies a nominal center wavelength, it is common for the actual central wavelength to vary by up to ± 5nm either side of the nominal central wavelength, C_p.

Figure 2 illustrates the output curves for LEDs with C_ps of 390, 395 and 400 nm central wavelengths. Note that these curves are similar in size and shape, but are shifted toward shorter or longer wavelengths.

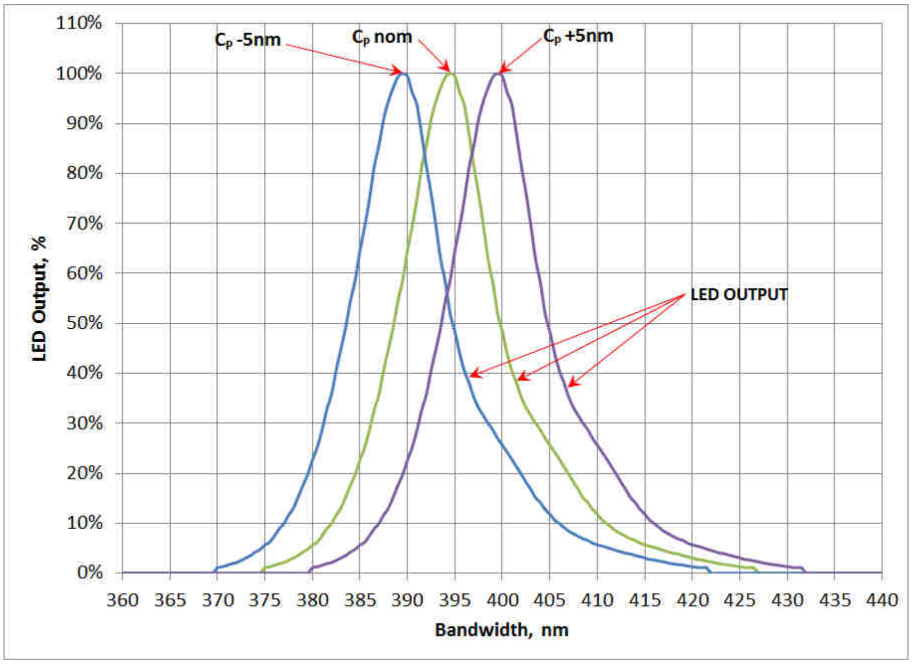


Figure 2. Output Spectra for Nominal 395nm C_p demonstrating spread of C_p. (Courtesy EIT LLC)

The central wavelength within a given lot of LED's can vary by + 5nm. It is necessary to extend the instrument optical response by +5nm so that only 2% of the energy falls outside the passband.

Figure 3 shows the effect on an L395 irradiance curve when the curve is displaced by + 5nm and the instrument response broadened by + 5nm. The result is a more suitable measurement response for L395 sources

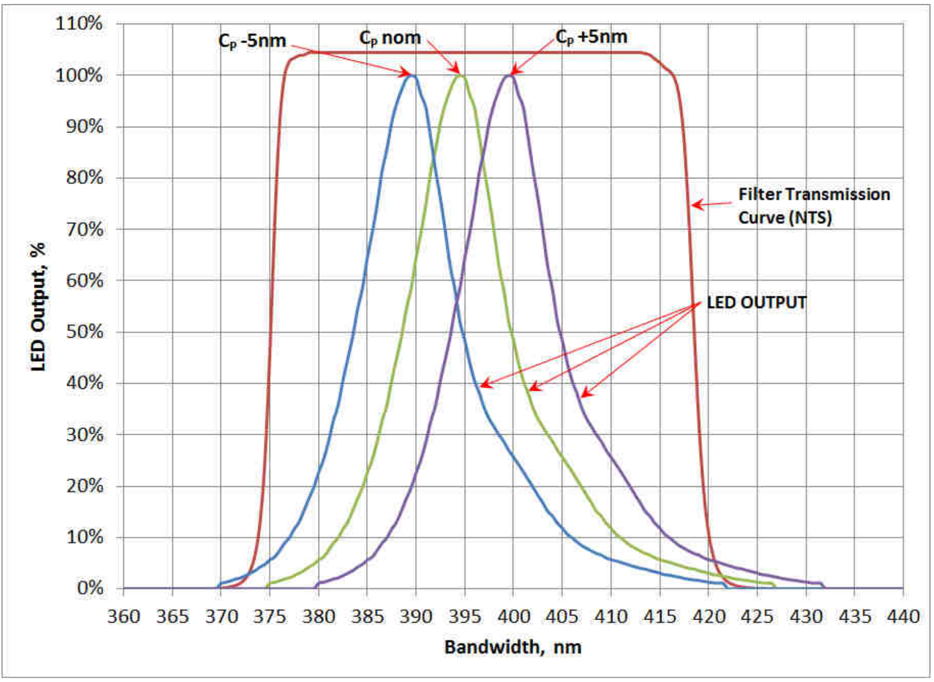


Figure 3. L-395 output spectra showing +5nm spread of Cp and instrument response necessary to capture 98% of the total energy (Courtesy EIT LLC)

4. UV Radiometer Design Goals

UV Radiometers are designed to meet a number of performance criteria and cost objectives. These include:

- Appropriate form factor (size and geometry) compatible with existing industrial process machinery.
- Adaptable to both a laboratory and production environments, and for use by a wide range of operators with varying degrees of training.
- Suitable robustness, since they must operate properly in harsh UV and elevated temperature environments.
- Requisite accuracy and reliability needed to establish and document a UV curing process in the lab
- Provide a platform for communication within a company and between their facilities
- Provide a platform for communication between suppliers and customers in the value chain

With regard to the instruments optical and electronic response characteristics, the shape and width of the instrument response may vary from instrument manufacturer to manufacturer. When considering the overall instrument response, including all components in the path of the UV, the wider the band the more difficulty in obtaining an overall rectangular instrument response.

Figure 4 below shows the spectral response (ideal) of a typical radiometer. Ideally, the response would be rectangular with a flat passband, very steep transition slopes from passband to out-of-band, and nearly zero response outside the passband. Such a response has proved nearly impossible to achieve.

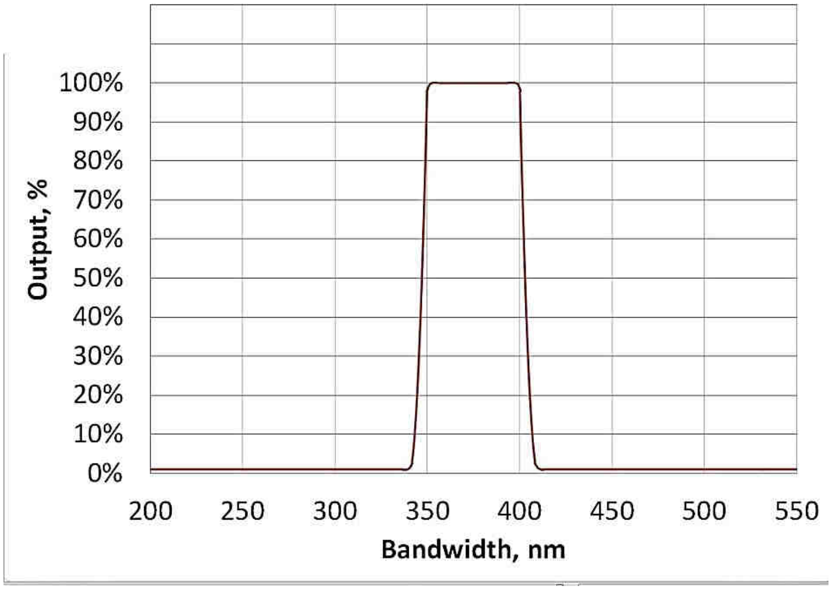


Figure 4. An ideal spectral response for a UV Radiometer (Courtesy EIT, LLC)

Most commercially available industrial radiometers describe their optical response in terms of their filter response and not the total optical response of all optical components that the energy passes through. Measurements can be challenging to make because optical component performance tends to be non-constant with wavelength, and susceptible to drift due temperature, time and variables often introduced during the data collection process in production or a lab environment.

Generically, there are several optical components in a typical radiometer. These can include:

4.1 The Protective Optical Window/Attenuator

In operation, all of the wavelengths from the UV source arrive at the outer surface of the Protective Window/Attenuator. The Protective Window functions to:

- Allow transmission of most wavelengths
- Protect the components inside the instrument from external contamination
- Attenuate energy levels which could damage the other optical components.

A typical Transmission % versus Wavelength curve for an Attenuator is shown in Figure 5.

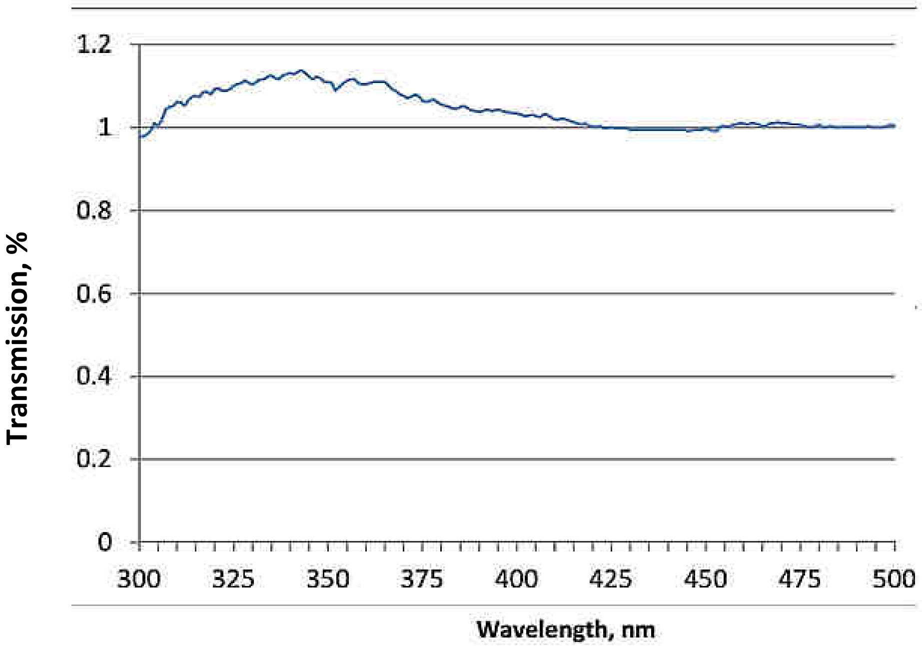
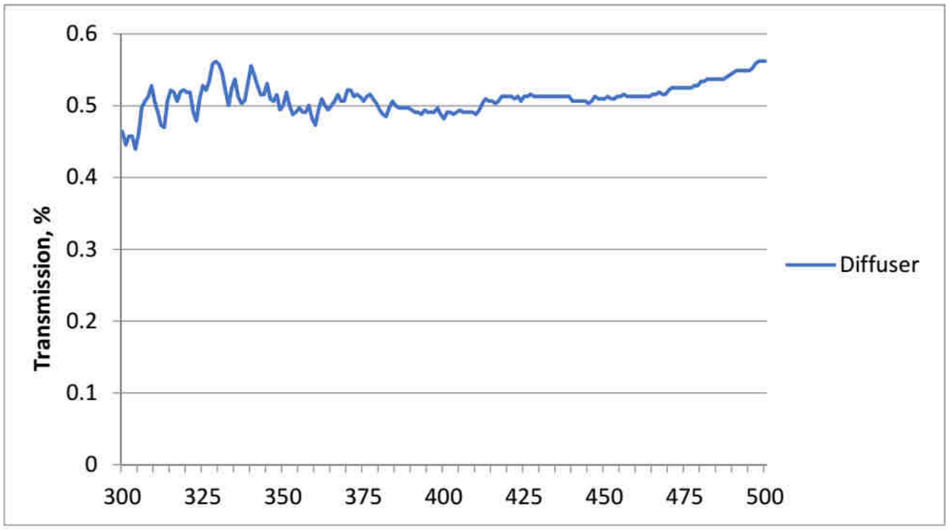


Figure 5. Transmission vs. wavelength for the protective window/attenuator (Courtesy EIT LLC)

4.2 The Optical Diffuser

Energy (UV, Visible and Infrared) which passes through the Protective Window falls on the Diffuser which transmits and diffuses the energy falling on its front face. It also provides Cosine Response for the instrument. Coatings are thought to react in a cosine manner. Energy arriving perpendicular to the coating surface are assumed to be able to penetrate further than energy arriving at other than right angles. Diffusers have transmission values which vary with wavelength. A representative Transmission %, vs Wavelength curve for a diffuser is shown in Figure 6.



Wavelength, nm

Figure 6 –Transmission % vs. Wavelength for Typical Diffuser (Courtesy EIT LLC)

4.3 The Optical Aperture

UV rays which pass through the diffuser are impinged on a small, opaque, (usually metallic) plate which contains a small hole near its center. The purpose of the aperture is to reduce total energy to the filter/detector combination to an acceptable level and to eliminate light leakage around the edge(s) of the filter(s). In the new UV LED radiometer design the aperture also performs an important optical function. The transmission of the aperture is spectrally flat in the new design and requires no optical compensation in the stack.

4.4 The Optical Bandpass Filter

Energy passing through the aperture then strikes a Bandpass Filter which is selected by the designer to transmit the wavelengths which are to be measured and to strongly reject all other wavelengths.

There are two distinct filter types used:

1. **Cut Glass Filter**: If Cut Glass type filters are used they usually have transmission values which vary substantially over the wavelengths of interest. A typical Transmission % versus Wavelength plot for a commonly used cut glass filter is shown in Figure 7. Note the lack of rectangular response.

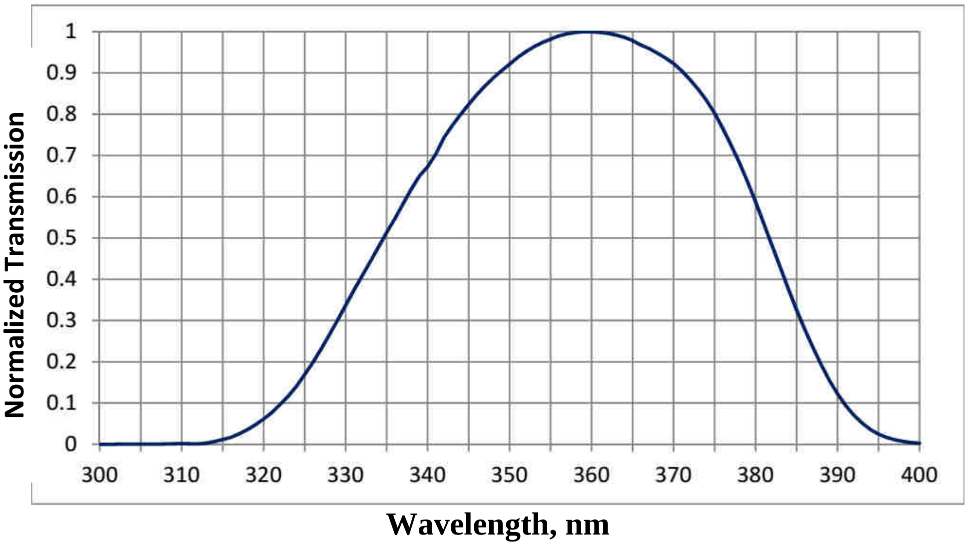


Figure 7. Transmission response for a typical cut glass filter (Courtesy EIT LLC)

2. **Color Interference Filter:**
   In some cases, Color Interference filters, as opposed to Cut Glass Filters, are used as the Bandpass Filter. These filters can be designed to provide good to excellent (rectangular) response in the passband and very good rejection outside it. Figure 8 shows the Transmission % versus Wavelength curve for a typical color interference filter. Note the excellent in-band response and out of band rejection, and steep transitions from passband to out of band.

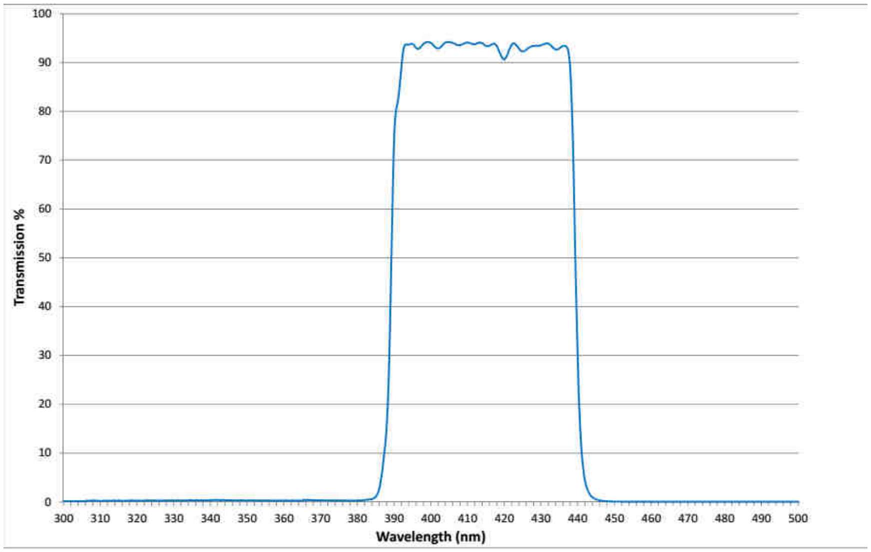


Figure 8. Transmission response for a typical color interference filter (Courtesy EIT, LLC)

However, there can be issues with the use of color interference bandpass filters. If the energy striking the front surface is not close to normal to that surface the response curve for that filter can be substantially altered. As an example, Figure 9 illustrates the response curves for such a filter when the energy incident on its front surface is at 0^0, 15^0 and 30^0 angle of incidence (AOI). Note the dramatic shift in cutoff wavelengths for angles larger than about 15^0.

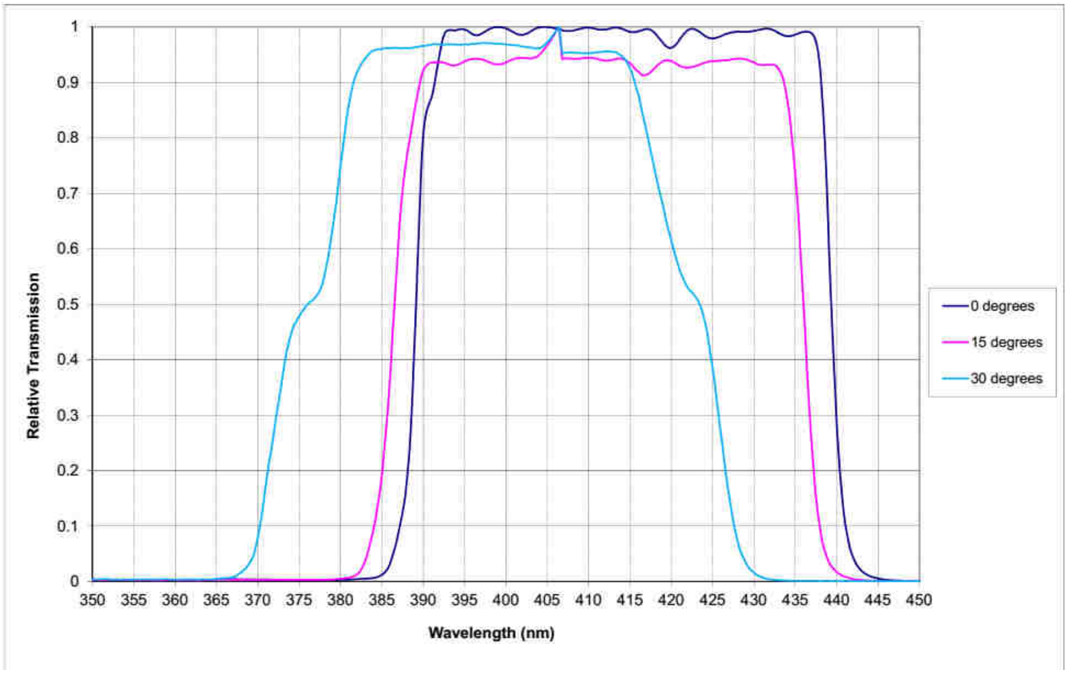


Figure 9. Color interference filter response for 0, 15, and 30 degree angles of incidence (Courtesy EIT LLC)

4.5 The Photodetector

Finally, UV energy exiting the bandpass filter strikes the photodetector where it is converted to a current which is proportional to the intensity of the UV striking it the photodetector characteristic is non-linear with wavelength.

However the responsivity of all photodetector types such as Ge, GAsP and silicon, generally resemble each other in the UV range. That is, they are non-linear with wavelength, generally decreasing in responsivity at shorter wavelengths.

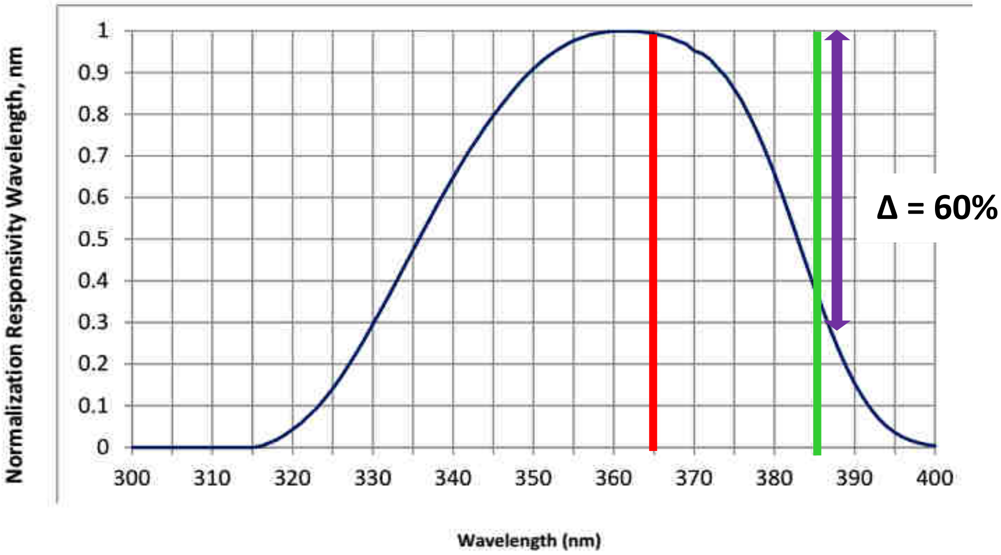


Figure 10. Response versus wavelength for optical stack with cut glass bandpass filter. Note the difference in values measured at two wavelengths; 365 nm (red) and 385 nm (green) (Courtesy EIT LLC)

Figure 10 provides a measured response curve for an actual radiometer which utilizes a cut glass filter. It is an instrument promoted as measuring UV the range from 320 nm to 390 nm. If an appreciable change in spectral make-up of the source being measured occurs there is a substantial change in the associated measurement. For example, if a line source, which is centered at 365 nm is measured and then compared to a 385 nm line source of the same intensity, there will be a 60% measurement error. Although the measurement is quite repeatable, to a few percent, the objective is to have an absolute measurement error of a few percent over the entire passband.

4.6 Color Interference Filter

It also is possible to use a color interference filter for a bandpass filter, but the results in this case are also less than optimum. This is because color interference filters only work well for small angles of incidence (AOI). In a traditional optical stack, if the AOI is larger than approximately fifteen degrees the filter characteristics are unacceptably deteriorated (See Figure 9).

Angles of incidence vary substantially because of the diffuser in the energy path which, because of scattering, produces many angles of incidence from 0^0 to 90^0. As a result, the rectangular passband curve becomes distorted because of the multiple angles of incidence created by the diffuser.

Radiometer manufacturers typically show only the spectral response of the bandpass filter alone and neglect optical response contributions by other components such as the photodiode, diffuser, protective window and attenuator. In the case of present day instruments, some of which use color interference bandpass filters, no provision is made for optical response changes caused by various factors including angle of incidence factors. In the case of cut glass bandpass filters, angle of incidence factors are not relevant. However, in both cut glass and color interference filter cases, the spectral response of the instrument is not rectangular, but it is desirable that it be so.

The resulting instrument response is substantially different from the filter response which manufacturers typically publish as representing the overall optical response of their instrument(s). While this practice does not prevent the instruments from being used in a relative measurement mode, the results obtained can be much different from the desired rectangular response and generally do not provide accurate irradiance and absolute energy measurements.

5. A New Approach: Total Optics Measured Response (TOMR)

EIT has patented a new optics design that incorporates <u>all</u> optical components in the instrument response. The new stack is capable of making absolute UV energy measurements over the spectral bands produced by UV LED sources.

These are identified as the “L” bands, and their center wavelengths, denoted C_p, are centered at 365, 385, 395, and 405nm as shown in Table 3. C_p may vary by as much as +5nm and still be within specification. The actual spectral distribution within an LED array may vary depending on how the LEDs array are binned

The measurement requirement for a given band is rectangular in shape and covers a range of approximately 50 nm for each band. The width of the band allows the total optical response to be very well controlled and to be repeatable.

Table 3. UV LED "L" Band Designations and measurement range (Courtesy EIT LLC)

EIT Band	Wavelength C_p	Measurement Range
L405	400-410nm	383-433nm
L395	390-400nm	370-422nm
L385	380-390nm	364-414nm
L365	360-370nm	343-393nm

Figure 11 shows the L395 band response for the LEDCure™ L395 instrument design.
Note that *this is an actual measured response reflecting all optical components in the instrument.*
Note that the response is essentially flat across all wavelengths associated with a 395 nm source.

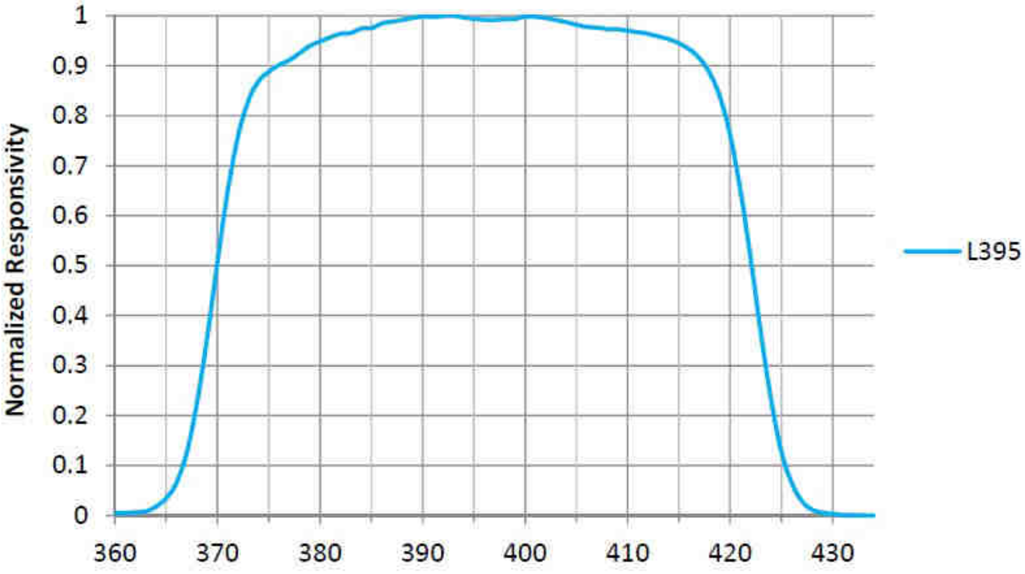


Figure 11. The L-395 Total Optical Measured Response (Courtesy EIT LLC)

Figure 12 shows the optical response curve for the L395 radiometer. The spectra for the LEDs used in an L395 source are imposed on it, and the upper, median, and lower limits for C_p are shown.

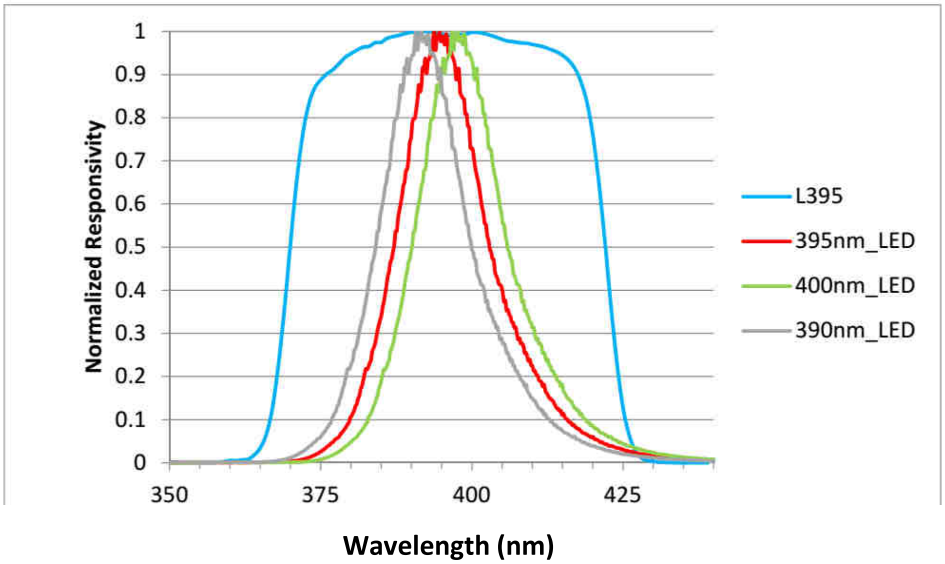


Figure 12. Optical Response Curve for L395 Radiometer with Lower, Median and Upper Limits of LED Spectra Shown (Courtesy EIT, LLC)

These instruments use newly developed and patented techniques which directly address the issues associated with obtaining rectangular optical response in the new radiometers. The radiometers are designed for measuring sources which use UV LEDs.

The L-Series Optics Design uses a new way to integrate the optical stack. The new L-Series optic stack design utilizes a specially designed color interference bandpass filter and addresses angle of incidence control.

6. Total Optics Measured Response (TOMR) Performance and Validation Tests

Figure 13 shows the results of testing two different LEDCure instruments on a 395 nm industrial LED source over 20 runs. The overall variation in the source irradiance was just under 1%. This was most likely due to variation in the applied power over the course of the 20 runs. When the two units were compared to each other, the ratio of the two units to each other was approximately 0.2%. For industrial UV measurement on a production source, the actual and ratio performance is very good.

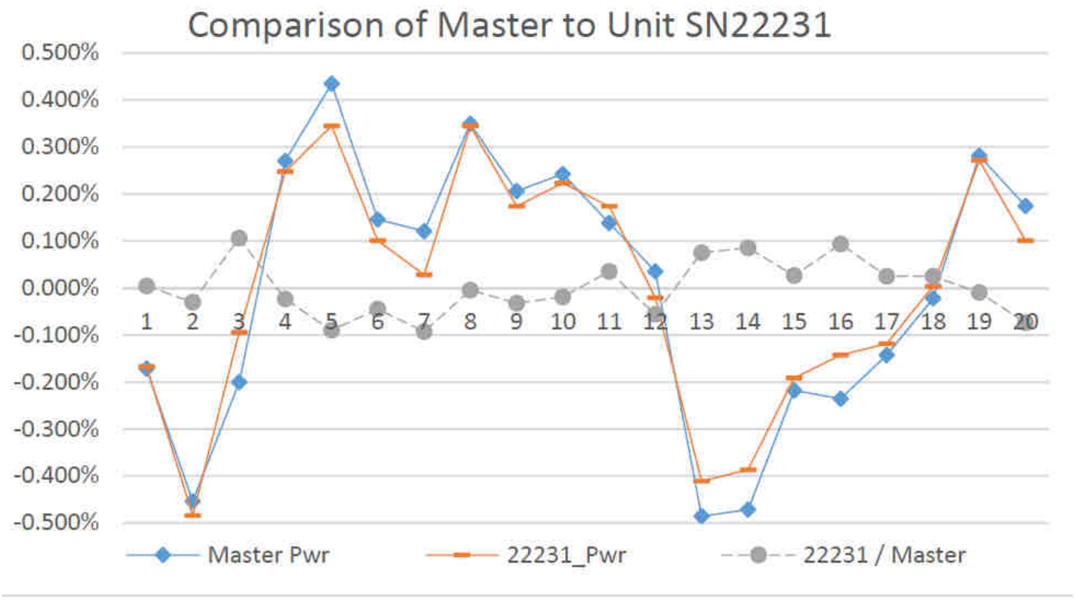


Figure 13. Comparison of two L395 LEDCure radiometers over 20 runs (Courtesy EIT LLC)

6.1 TOMR Field Test Results

In addition to successful in-house testing, the TOMR approach has been validated in a number of field trials by UV LED source manufacturers.

Figures 14-16 illustrate the performance of an the LEDCure™ L-395 in tests conducted by Phoseon Technology. These findings show that the instrument exhibits excellent spectral response across measurements made with 385nm, 395nm and 405nm lamps

The instrument’s ability to discriminate between LED sources is demonstrated by the very low response of the L-395shown to a 365nm array, showing that the spectral response has a steep skirt. The data also shows very consistent peak irradiance and energy density measurements when at scan speeds were varied between 1.2 and 6.0 meters/minute. Finally, repeated measurements showed very little variation, and good correlation to a NIST traceable meter from another manufacturer.

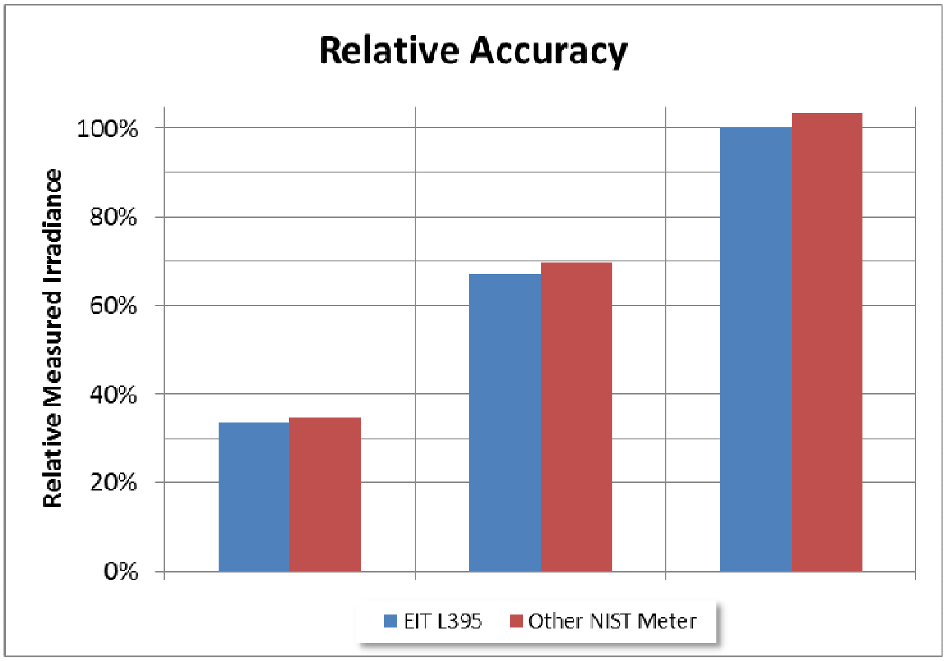


Figure 14: Comparison of irradiance values (Courtesy Phoseon Technology)

Figure 14 depicts testing conducted by Phoseon Technology using a 395nm UV LED source calibrated to 16W/cm² using the EIT L395. The UV LED source was then measured with another NIST traceable radiometer. The two radiometers matched to within 4% at different irradiance levels

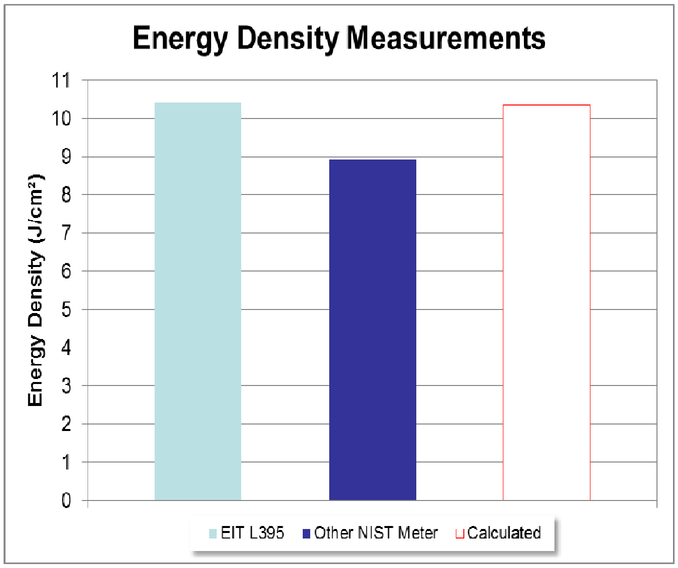


Figure 15. L-395 comparison of energy density values (Courtesy Phoseon Technology)

Figure 15 provides measured results from a second set of tests that compare the EIT L-395 TOMR radiometer to another brand of NIST traceable radiometers with respect to the expected value. The TOMR instrument differed from the calculated value by less than 1%, while the alternative NIST traceable radiometer differed from the calculated value by more than 13%.

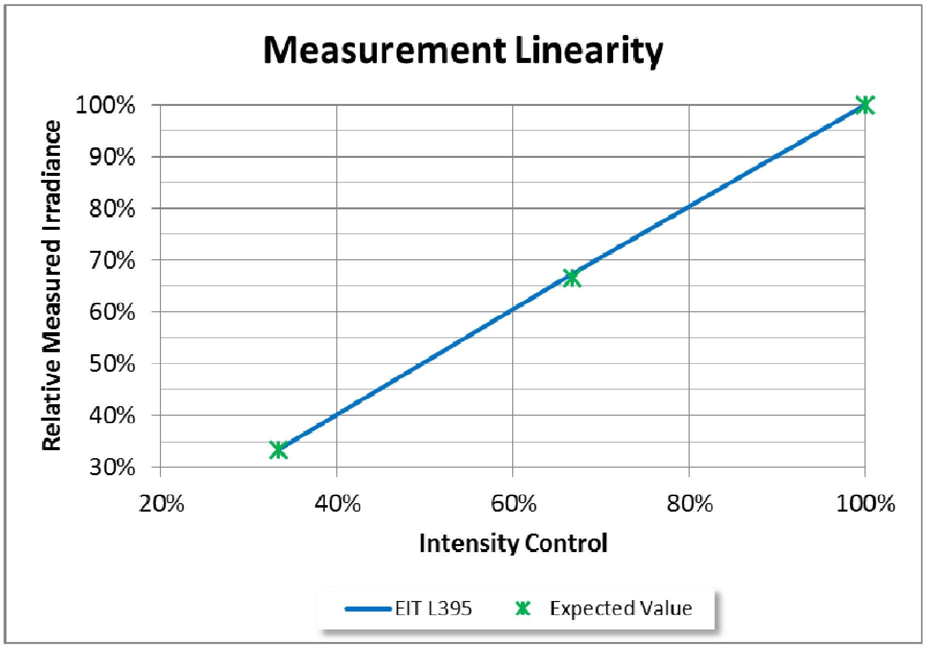


Figure 16. Instrument linearity test results (Courtesy Phoseon Technology)

Figure 16 shows the results of a third set of performance tests. This test, designed to measure the instruments linearity over a broad range of intensity shows that the EIT L395 TOMR radiometer, has exceptional linearity across a 3:1 dynamic range.

6.2 Comparison of LEDCure™ Readings to a Primary Standard

In performance testing conducted by Excelitas Lumen Dynamics Group Incorporated (part of the Excelitas Technologies Corporation), an EIT LEDCure™ L-395 was compared to a primary calibration standard. The measured difference at different distances is summarized in Table 4.

Working Distance (mm)	**Primary Standard: Integrating Sphere (W/cm^2)**	**LEDCure L395 (W/cm^2)**	**Difference (%)**
5	9.01	9.23	2.4%
10	7.74	7.74	0.0%
15	6.66	6.63	-0.5%
20	5.74	5.83	1.6%
25	5.04	5.08	0.8%

Table 4: LEDCure Compared to Primary Standard. Testing performed by Lumen Dynamics Group Incorporated, part of the Excelitas Technologies Corporation.

Additional testing of the LEDCure™ L395 unit was also performed by Integration Technologies and Ushio.

7. Summary

The past decade has been an exciting time for UV curing since LEDs have emerged as an attractive alternative to mercury-based lamps for an ever increasing array of applications. While those who embraced LEDs only a few years ago were called rebellious early-adopters, today LEDs are mainstream technology for spot curing adhesives or small to medium format digital printing. As success stories continue to mount, we expect the penetration of UV LEDs into these markets to continue, and for the uses of LED to expand to other markets where the longevity, stability, safety and other benefits of LEDs can be harnessed. However, these markets are expected to present more difficult technical challenges such as tighter process windows, larger size arrays, higher irradiance and energy density requirements, or more complex surface geometries.

These more demanding cure applications will require an even greater need to establish and maintain tighter process windows, where the benefits of “using a bigger hammer” may not be sufficient to avoid defects and failure. Establishing and maintaining these processes will require a more rigorous approach to UV process measurement, using devices specifically designed to measure UV LED output.

To address these needs, new L-Series bands are proposed specifically for UV LED sources, and a patented Total Measured Optic Response (TOMR) approach has been commercialized. With a TOMR approach, all of the optical components in the radiometer are taken into account in the overall instrument response. At this time, LED radiometers using L365, L385 and L395 bands are currently being shipped in instruments with standard and data profiling configurations. Field testing has shown the L395, L385 L365 to have the exceptionally consistent run-to-run, source-to-source, and unit-to-unit performance needed for this new generation of UV LED curing applications.