Measurement of Ultraviolet Energy for UV LEDs

Proposed Band Definitions

Joe T. May
EIT, LLC
Sterling, VA
7/1/2015

INTRODUCTION

The issue of how to measure LED generated UV energy has become increasingly important as LED based UV curing systems have become more widely used. Existing UV measurement systems can be made to work acceptably well with conventional mercury based UV sources. However, there have been numerous questions regarding the accuracy and even validity of UV measurements made with traditional measurement instruments on LED based UV systems.

This article explores the issues involved in measuring UV energy generated by both mercury lamps and UV LED's. We describe the fundamental challenges, propose some basic definitions for UV LED sources, and illustrate measurement limits to achieve commercially acceptable accuracy in in the single digits for UV LED measurements. We conclude that accurate measurements of UV LED energy can be made if inappropriate methodology is used.

This is the first of two articles. The second article will describe how to implement the principles discussed in this paper.

Measurement of UV Energy from Mercury and LED Sources

1. UV From Mercury Sources

The use of Ultraviolet (UV) energy for industrial processes has been well established. Traditionally, UV energy has been generated using an electrical discharge through, or RF excitation of, an evacuated quartz tube which contains a small amount of mercury. The resulting emission spectrum contains a continuum with relatively large discrete energy peaks at various wavelengths characteristic of mercury. Figure 1 shows the typical emission spectrum of a medium pressure mercury lamp. The peaks at 365 and 405 nanometers (nm) and the very small continuum are characteristic of mercury only sources.

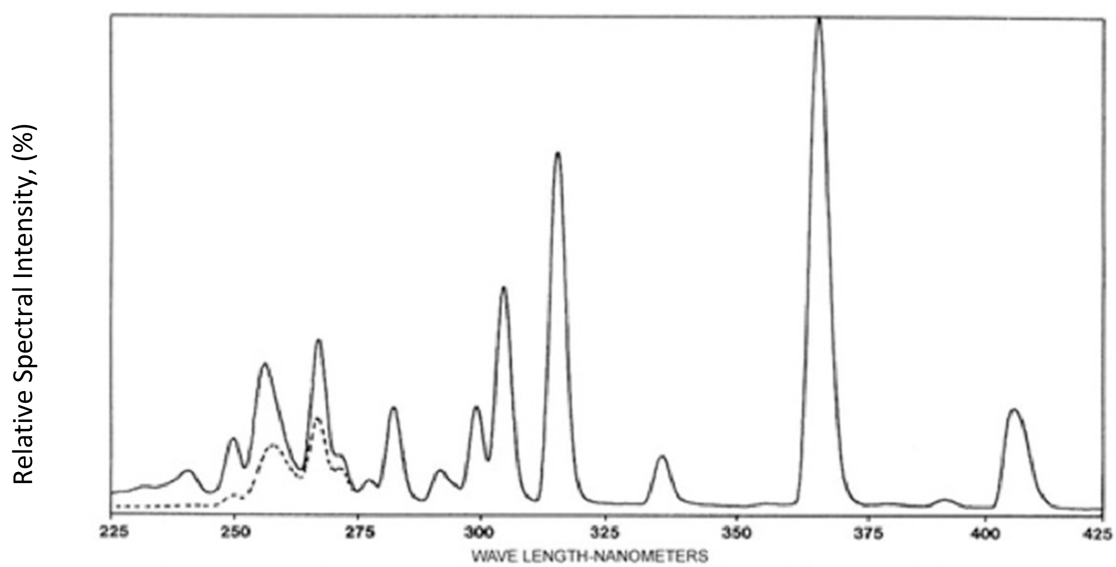

Figure 1 – Typical Medium Pressure Mercury (Hg) Lamp Spectra [1]

Please note that the dotted line represents the output of ozone free quartz.

Adding a metal halide alters the spectral distribution, particularly at longer wavelengths, although the original mercury peaks still predominate. Figure 2 illustrates the output of such an additive lamp. Note the increased emissions between ≈ 350 to ≈ 400 nm.

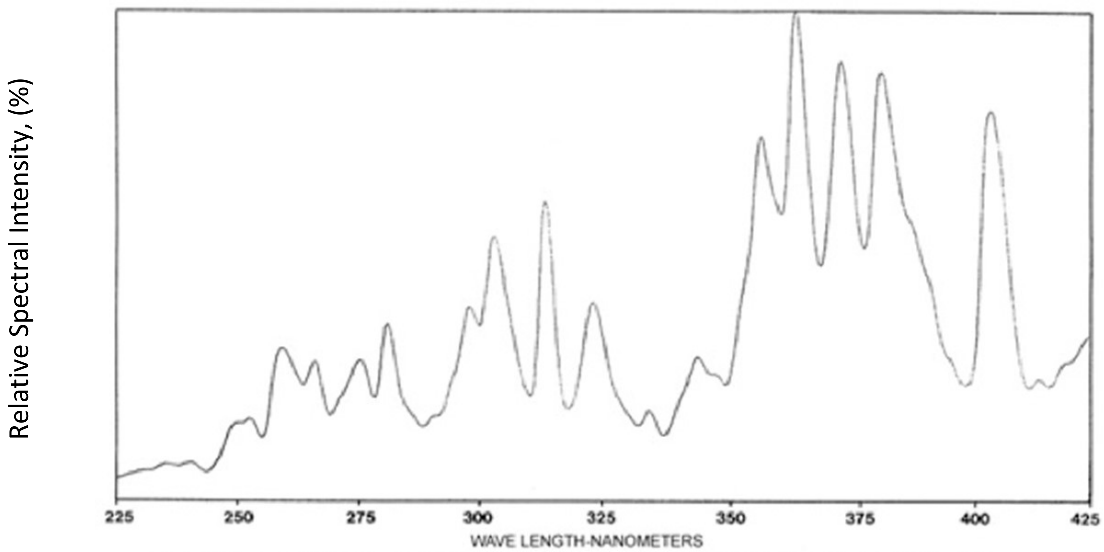

Figure 2 – Typical Spectra for Mercury Lamp with Iron (Fe) Additive [2]

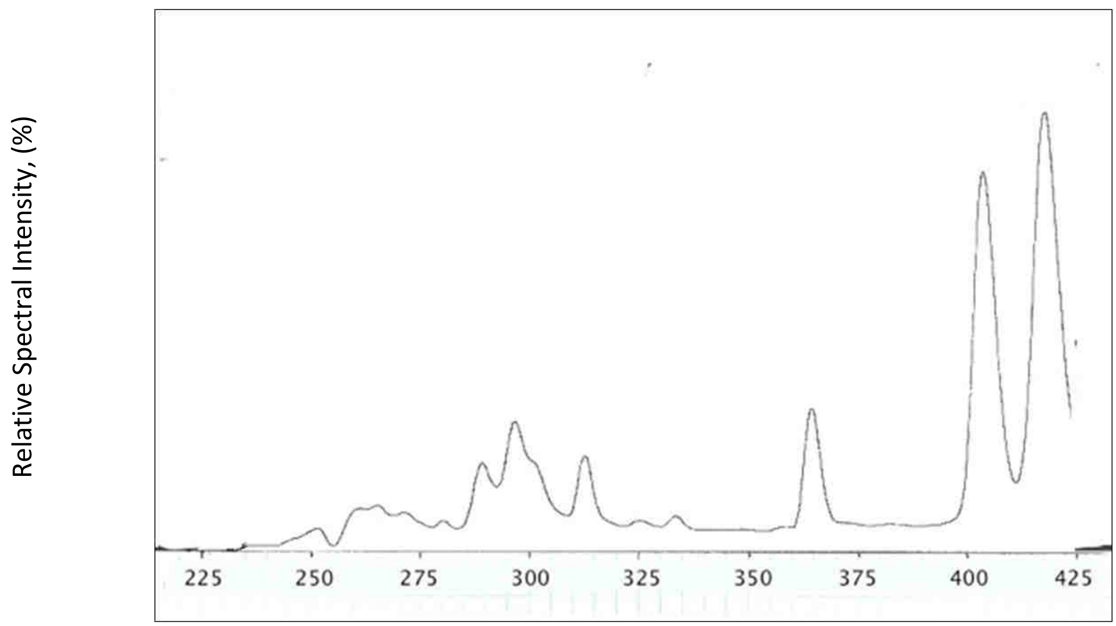

Figure 3 – Typical Spectra for Mercury Lamp with Gallium (Ga) additive [3]

If the additive to a mercury lamp is gallium (Ga), the amplitudes of typical mercury lines are reduced, particularly at the 365nm peak. In addition, several much stronger peaks are generated beyond 400nm. Note there is little continuum in Figure 3 which shows the spectra from a Mercury-Ga lamp.

2. Measurement and Definitions

Measurement of UV energy from a medium pressure "mercury only" source primarily 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. (Note: "UVV" in this paper denotes wavelengths in UV-Visible transition range and not the so called short wavelength "vacuum" UV). There may be minor variations in the definitions of designated UV bands. For this paper we are defining "UVA" as 315-400 nm, "UVB" as 280-315 nm, "UVC" from 200-280 and "UVV" from 400-450nm. See Table 1.

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

Table 1 – Mercury Spectral Band Definitions

Different lamp types (Hg, Hg-Fe, and Hg-Ga) emit different signature wavelengths. These wavelengths and the associated energy in them, are of interest because UV polymerization has been shown to be wavelength dependent. Thus, matching the wavelength and the intensity of the UV source to a given formulation is useful in creating a satisfactory UV curing process. For example, the 390-400 nm band may be much more effective in dissociating the photo initiator into radicals than shorter or longer wavelengths. 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.

3. LED UV Sources

High energy light emitting diode (LED) UV sources have become much more common since the early 2000's. Their operational principles and their spectral emission characteristics are much different than conventional mercury light sources. The spectral distribution for a typical commercially available 395nm

LED source is shown in Figure 4. 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 light source. Note that 98% of the power is emitted in the range between 377nm to 422nm which is many times the width of an individual mercury spectral line.

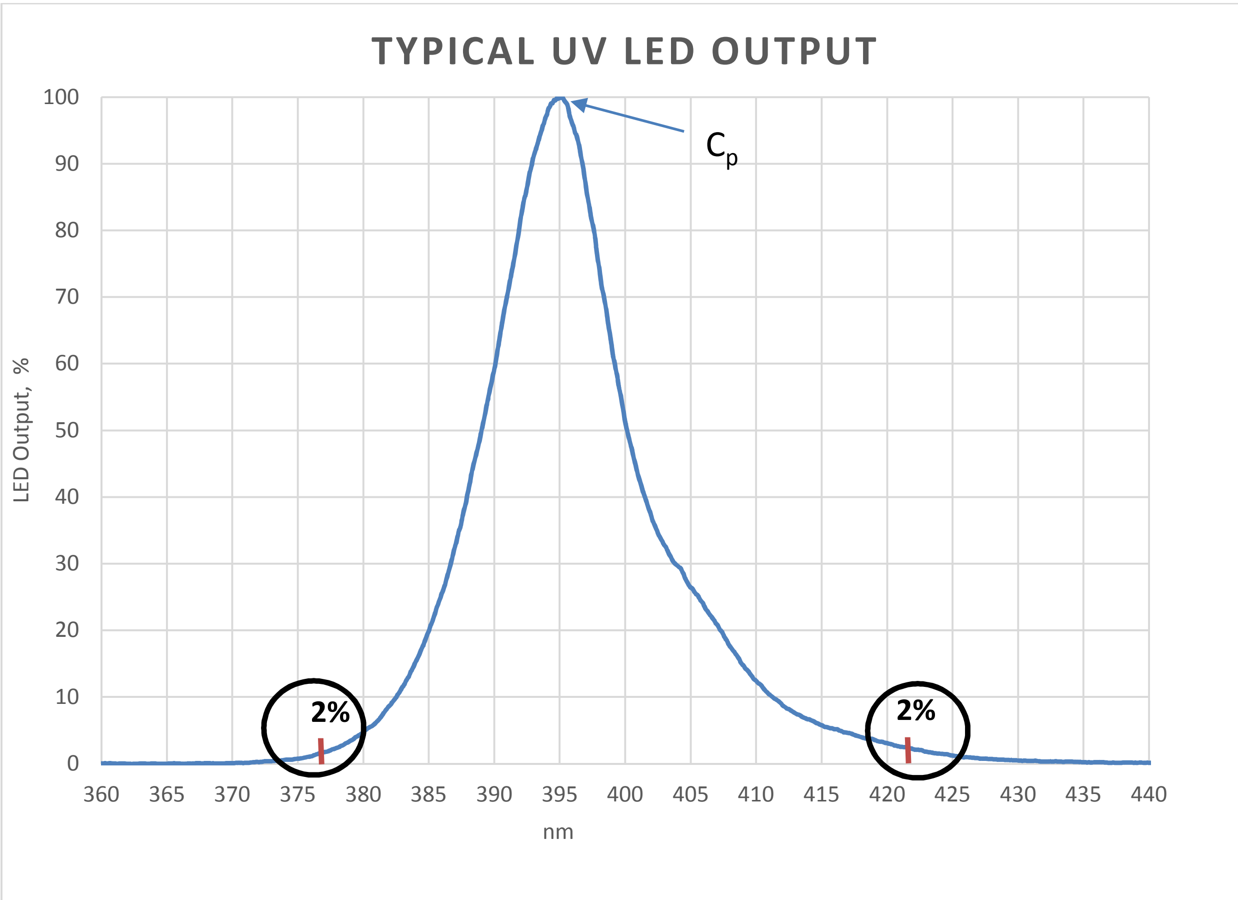

Figure 4 – Typical 395nm UV LED Spectral Output (4)

4. Commercial UV LED Curing Systems

Commercial LED curing systems are comprised of multiple LED devices mounted on a common substrate in an array that can vary in shape, but is most often linear or rectangular. Light source manufacturers use proprietary methods to select or "bin" the individual "devices" 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. Manufacturers use different approaches to direct the UV output such as deciding whether to add optics or not and to control the power/heat to and from each 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). However, because of manufacturing variabilities in the devices, and operating conditions in the assembly, the C_p of any LED in the assembly can typically vary by $\pm$ 5 nm. Selecting UV LED 'devices' within a very tight allowable window of only a few nanometers would increase the assembly price. Some formulators have suggested that there may also be some advantages to having a mixture of different devices with the C_ps uniformly centered +/- 5 nm from each other.

The amount of permissible variation in spectral output acceptable to an individual manufacturer assembling commercial UV LED curing system has important consequences. Figure 5 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.

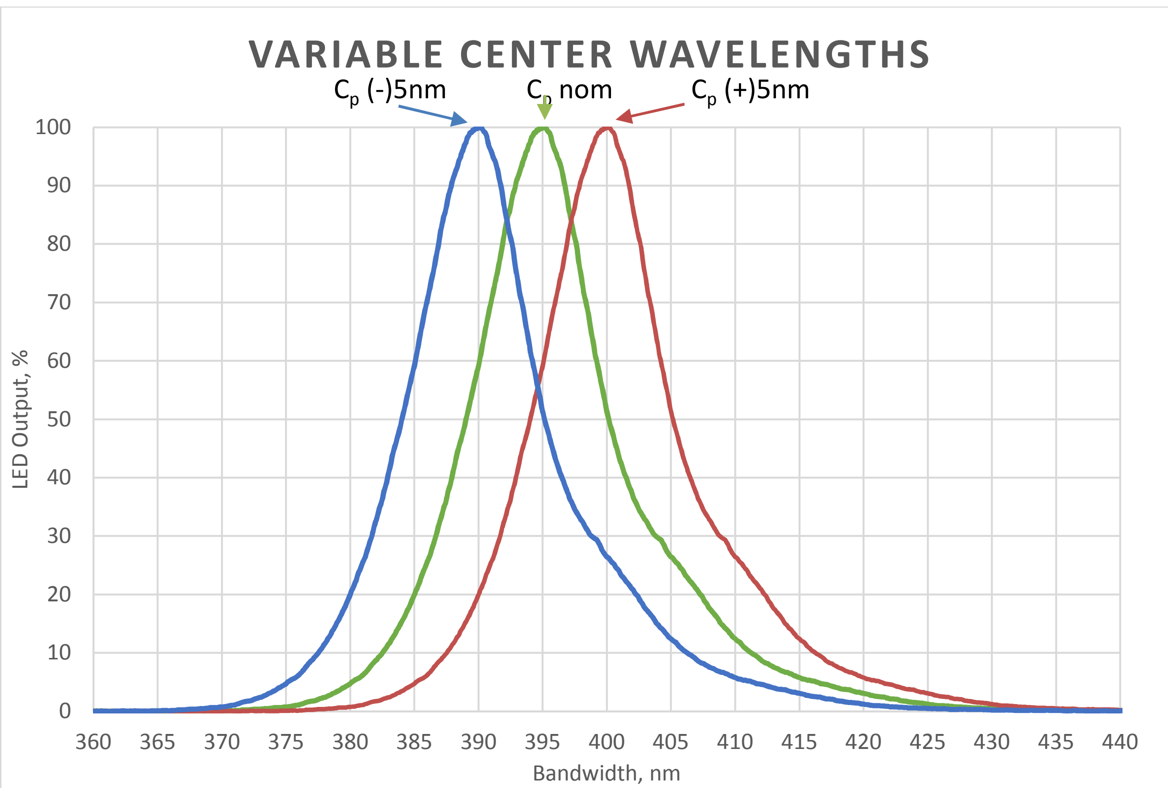

Figure 5 – Output Spectra for Nominal 395nm Cp- Demonstrating Spread of Cp. [(5)]

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 $\pm$ 5nm either side of the nominal central wavelength, C_p.

5. Proposed Definition of UV LED Bands

EIT proposes an identification system which uses Band Name Identifiers to describe LED curing systems by their nominal central wavelengths as shown in Table 2 below.

Band Name Identifier	Cp Wavelength Range
L 415	410-420nm
L 405	400-410nm
L 395	390-400nm
L 385	380-390nm
L 375	370-380nm
L 365	360-370nm

Table 2 – Proposed UV LED Bands

The "L" is intended to denote an LED type light source, while the numeric portion denotes the nominal central wavelength of the source in nanometers (nm). The LED notation is intended to be analogous to the popular mercury lamp band UVA, UVB, UVC and UVV notations. .

There are several reasons for defining the UV bands by a nominal central wavelength, C_p, with a $\pm$5 nm range around the nominal central wavelength.

- 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.

6. Measurement of LED UV Sources

Compared to traditional mercury-based UV sources, LED UV sources are relatively narrow band. However, mercury sources produce multiple spectral lines which are each a few nanometers wide while the currently available LED UV sources produce UV in a range with a distribution 45-55nm wide. (See Figures 1 and 4 for a visual comparison of typical mercury and LED spectra).

The total intensity of a source is obtained by summing, or integrating the area under each element of the intensity curve along the entire spectral range of the source. In Figure 6, a typical LED output curve and a typical instrument response curve are shown. The total energy in the band is obtained by convolving the LED curve with the total instrument responsivity and numerically integrating, in one nanometer increments, the resulting values curve.

As an example, Figure 6 illustrates a source where the central wavelength is approximately 395nm and the irradiance has decreased to 2% of peak at about 377nm and 422nm. Thus, if a measurement of the UV energy is made with a radiometer which has a rectangular instrument responsivity (not just the optical filter) from 377 to 425nm, then the irradiance measurement will capture nearly all of the energy emitted from that LED.

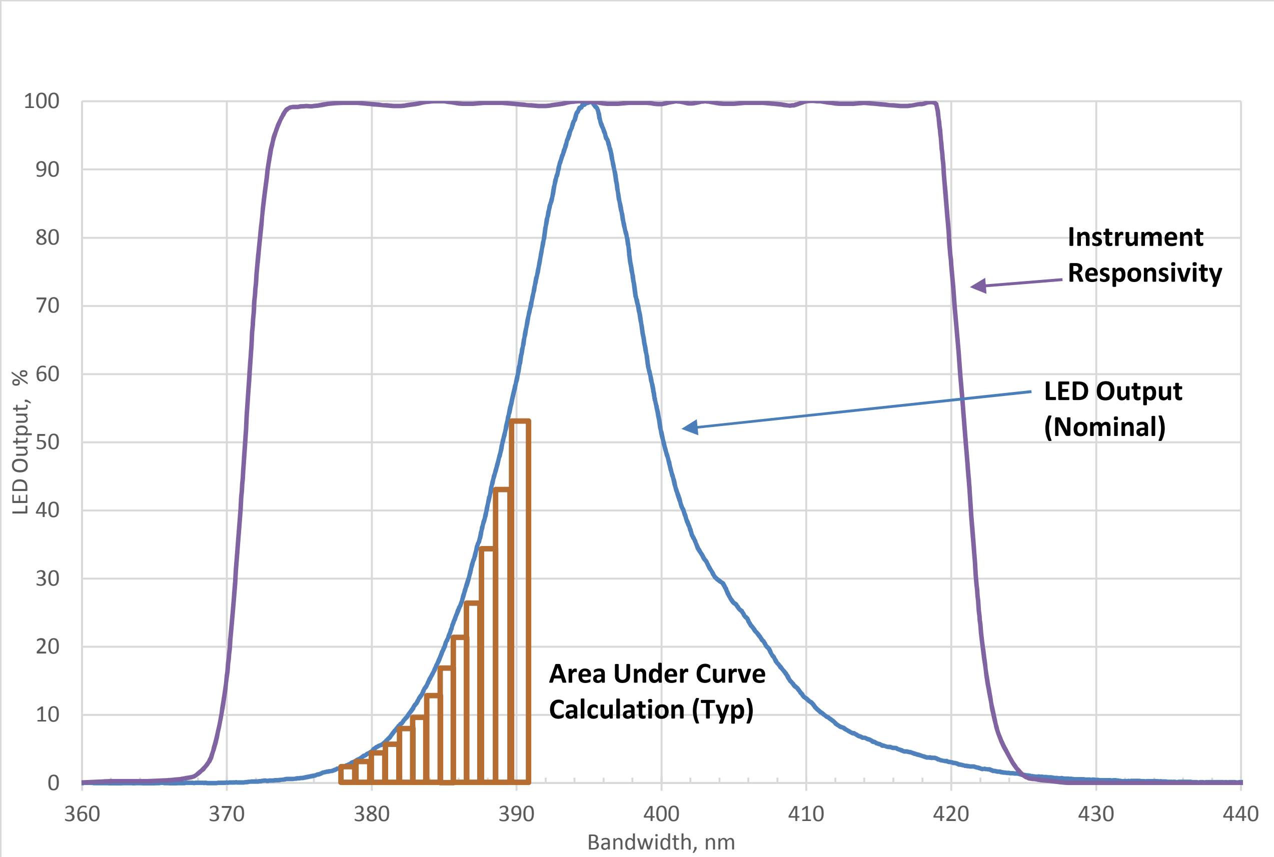

Figure 6 – Typical LED Spectral Output – Cp ≈ 395nm and Typical Optical Response Curve Required to Capture 98% of Energy [(6)]

However, because central wavelength within a given lot of LED's can vary by + 5nm, it is necessary to extend the original optical responses by +5nm so that only 2% of the energy falls outside the passband. In fact, the measurement error will be less because calibration methods can be used to compensate, at least partially, for such errors. 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 7 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.

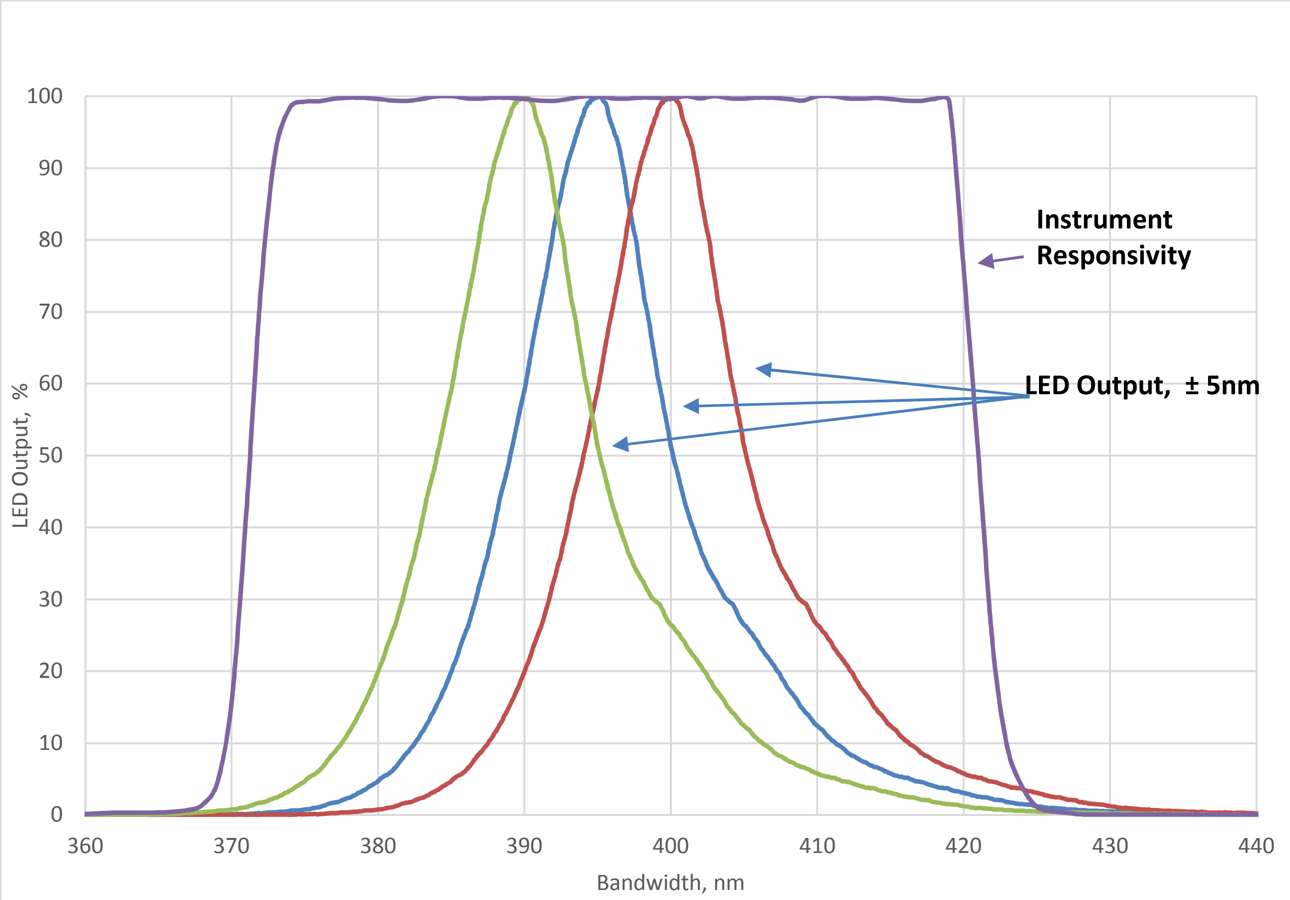

Figure 7 – L395 LED Output Spectra Showing ± 5nm Spread of Cp Along with Required Instrument Response to Capture 98% of the Total Energy [7]

Although in this example, the chosen band was L395the same approach can be used for the L365 through L415 bands. Figures 8, 9, 10 and 11 shows the different bands with corresponding instrument responses.

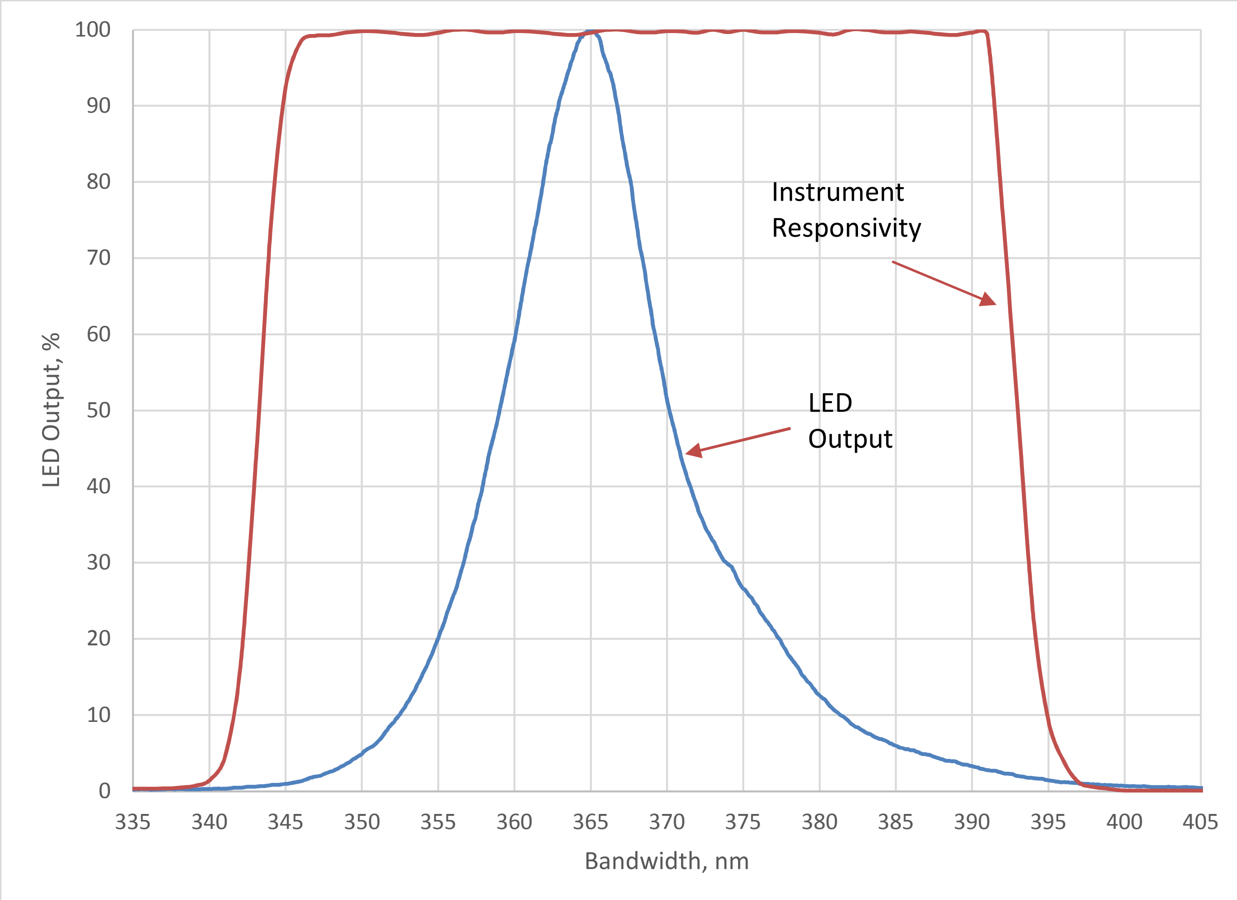

Figure 8 – L365 LED Spectra and Associated Instrument Response [8]

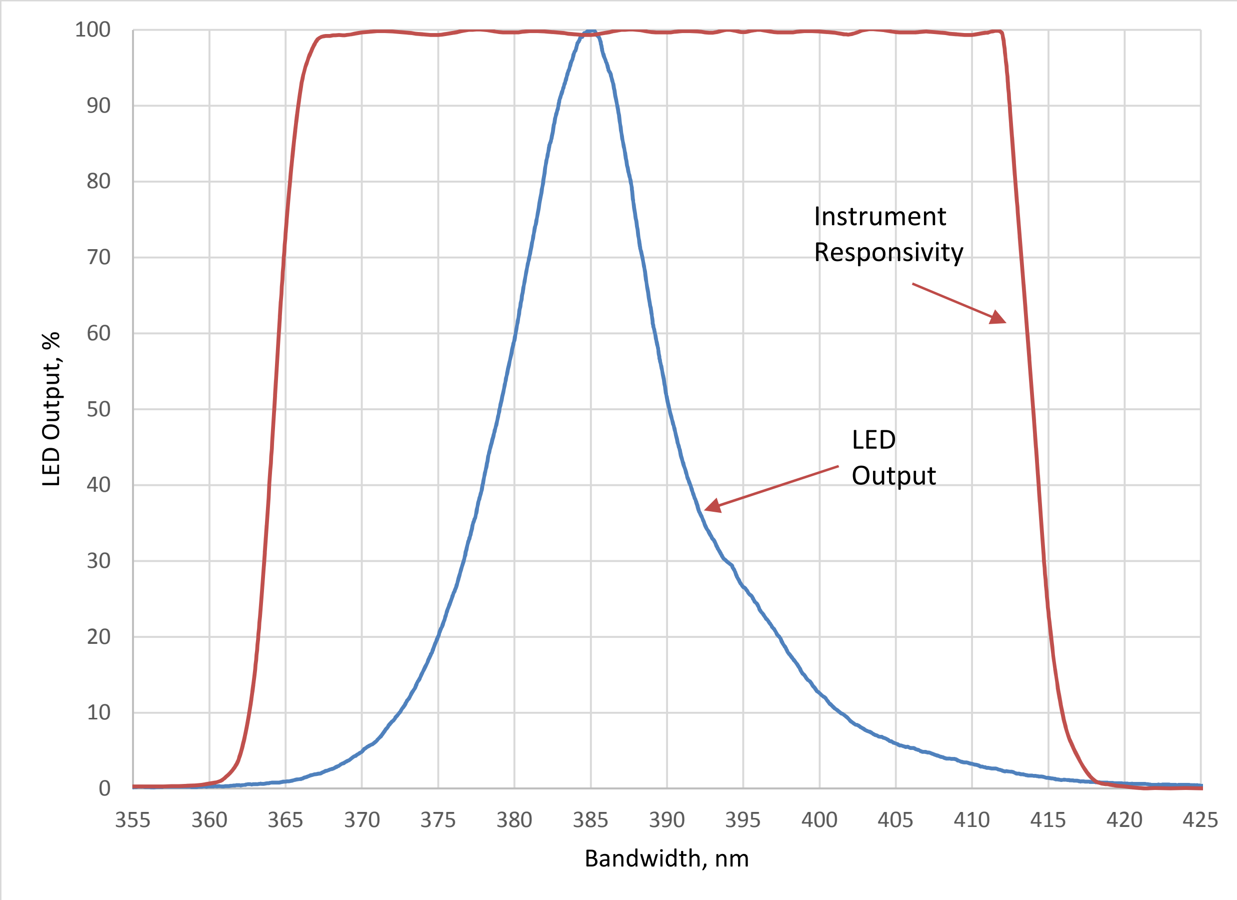

Figure 9 – L385 LED Spectra and Associated Instrument Response [9]

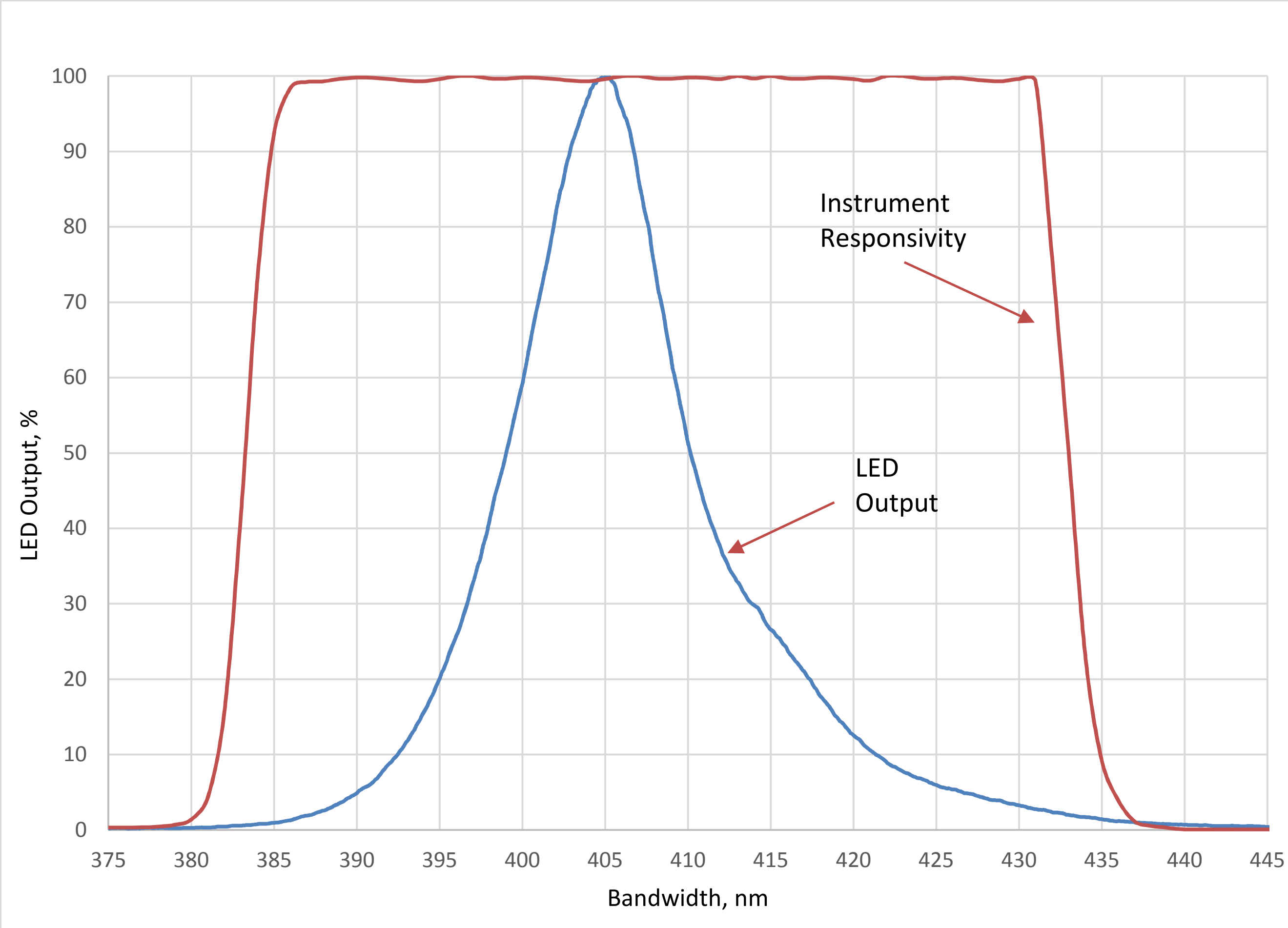

Figure 10 – L405 LED Spectra and Associated Instrument Response [10]

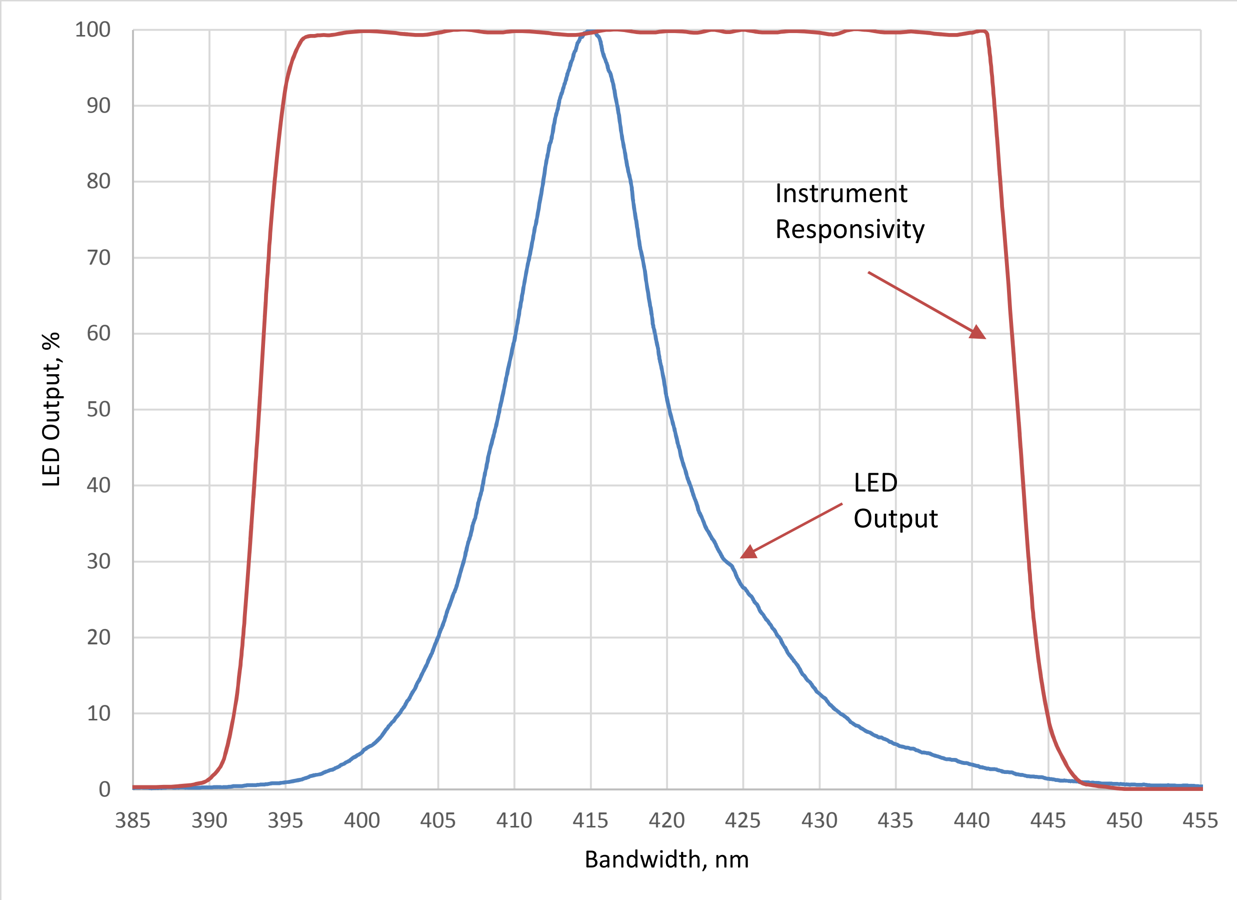

Figure 11 – L415 LED Spectra and Associated Instrument Response [11]

Summary

UV energy generated by traditional arc and microwave mercury lamps can be measured satisfactorily using existing methods that utilize non-linear but repeatable and matching optical characteristics. This is possible because most of the UV energy in the mercury spectra resides in a few, large, narrow, discrete bands that allow the measurement instrument to be calibrated to those few wavelengths. This approach can be made to work acceptably well on mercury sources.

Matching optical components allows results obtained from multiple UV sources to be compared and those results used to relate measurements made at one physical location with those made at another as long as the sources have comparable spectra.

However, the same non-linear measurement methods do not work as well with UV LED light sources. This is so because of the variation in wavelength distribution of individual LED's and because the LEDs in an array can, and do, have various central wavelengths. In fact, manufacturers typically specify a UV source assembly by a central wavelength, plus or minus five nanometers. (e.g., 395nm ± 5nm). This requires the response of a UV measurement system to be broad enough and sufficiently flat enough to capture the majority of energy, out to the 2% point, and to have uniform response in the passband.

As an example, Figure 12 shows a spectral distribution of an L395 source and the rectangular measurement bandwidth required to capture 98% of the UV energy under that curve. Note that the overall optical response has been extended a total of ten nanometers to accommodate up to ten nanometer spread of C_p. Similar methods work well for other L bands.

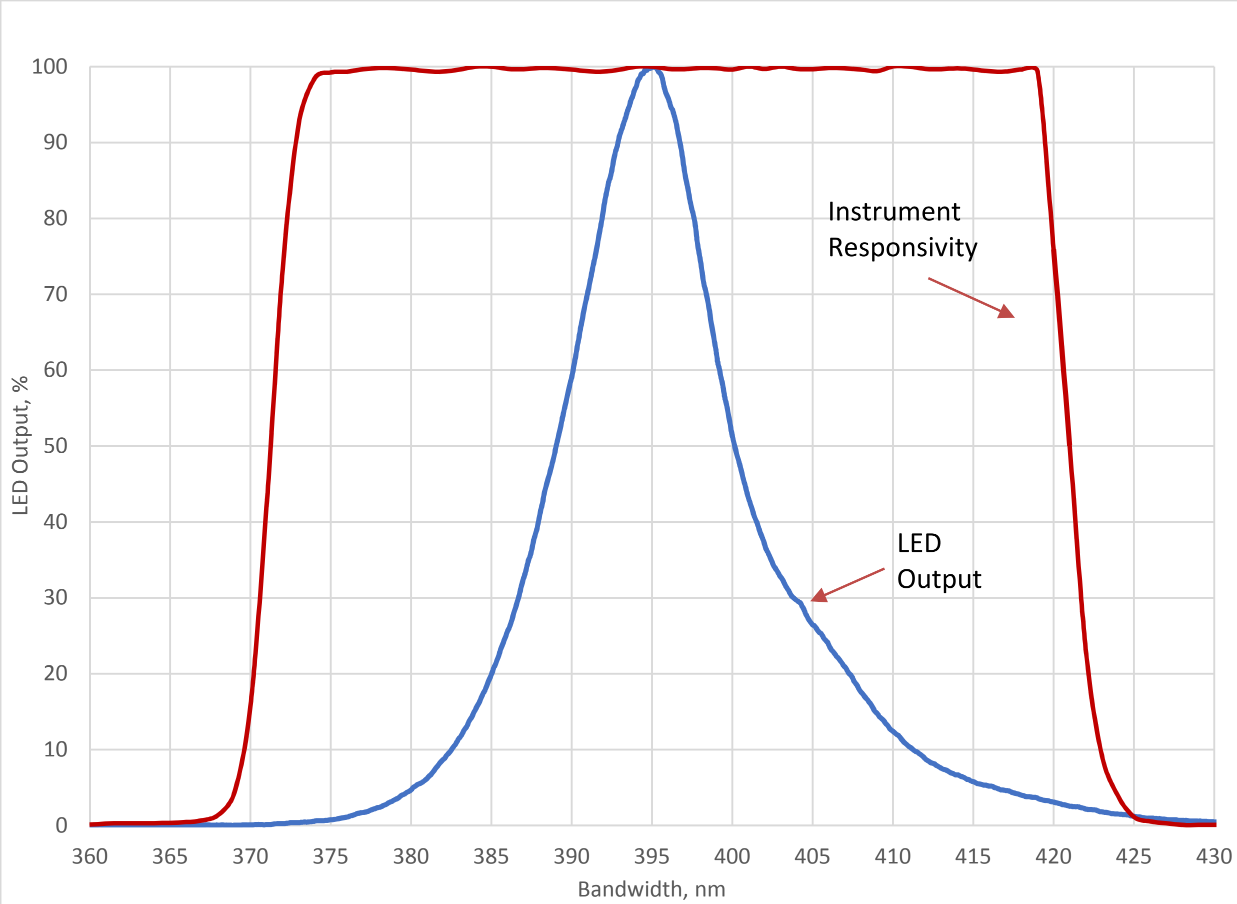

Figure 12 – L395 LED Spectra and Associated Filter Response Required for Capturing 98% of Band [12]

Conclusions

- The output of UV LED sources can be measured accurately. However, this requires a different approach from the measurements made on traditional mercury lamps.
- EIT proposes defining new LED UV bands centered at 365, 385, 395, 405, and 414nm and denoting these as L365, L385, and so forth. The resulting measurement bandwidth would be approximately 50nm wide. This approach permits greater measurement accuracy and enables better determination of the amount of energy in a specific bandwidth.
- Good process control requires accurate knowledge of the wavelength and quantity delivered/available of UV in the spectral region required for proper curing. The methodology described in this paper provides this important process information.
- This is the first of a two part series of articles. The second paper will address implementing the principles discussed in this paper into a measurement system

Sources and Acknowledgements

1. Courtesy Western Quartz Products, Paso Robles, CA
2. Courtesy Western Quartz Products, Paso Robles, CA
3. Courtesy Western Quartz Products, Paso Robles, CA
4. EIT, LLC, Sterling, VA
5. EIT, LLC, Sterling, VA
6. EIT, LLC, Sterling, VA
7. EIT, LLC, Sterling, VA
8. EIT, LLC, Sterling, VA
9. EIT, LLC, Sterling, VA
10. EIT, LLC, Sterling, VA
11. EIT, LLC, Sterling, VA
12. EIT, LLC, Sterling, VA