

# Characterizing the Output and Curing Capabilities of Semiconductor Light Matrix (SLM) Sources

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Solid-state UV emitters, such as UV LEDs, UV laser diodes, or Semiconductor Light Matrix (SLM) technology promise to alter the discussion of how UV materials are cured in a manner similar to the way the microwave oven has transformed the way we talk about cooking. Just as a bowl of popcorn may look and taste identical when cooked either way, so will UV coatings look and perform identically whether cured with conventional medium-pressure mercury lamps or with solid state devices. This will also require a new language when we describe the UV process. Since it will be just as inappropriate to describe cure in terms of watts/inch or specify measurements made with a LightBug® as it is to ask what temperature the microwave oven needs to be set for popping.

This paper is divided into three parts. First a description of the light output and related characteristics of semiconductor light emitting diode sources, and second a cursory comparison of how these sources behave in some representative UV curing processes. Finally, how these new UV semiconductor sources will affect photochemistry and enable new curing applications.

## A Photon is Just a Photon

UV curing reactions are driven by “light” that can be described using several parameters that affect the reaction; wavelength, peak irradiance, and “dose” (or energy density) related to the time of exposure. In purely photochemical terms these are the only variables regarding the UV source that matter. The manner in which the light is produced is irrelevant to the chemistry. For example, exposing of a coating to 365nm UV light at 200mW/cm<sup>2</sup> peak irradiance for 30 seconds produces the same effect whether the UV is produced by an arc lamp, microwave lamp or semiconductor device. A photon is a photon, and from the perspective of the photo chemistry the source is a black box.



**Figure 1.** UV Light Source is in essence a black box.

This is not to say that heat, stability of the light over time, and other factors related to photon production do not affect the process – they do. The costs to purchase and operate a UV source are also important – sometime critical to a project’s viability. But these factors are separate from the interaction of light with the photoinitiator.

## Part I. Describing the UV Light Source “Black Box”

### 1. Spectral Output

The most striking difference between Semiconductor Light Matrix (SLM) technology and their mercury lamp brethren is the narrow spectral output that characterizes SLM technology.

Following is the actual emission spectra of a commercial UV semiconductor device (Phoseon RX 10) measured using a spectral radiometer at an overall intensity of 1500mW/cm<sup>2</sup>.

The output is a single “monochromatic” peak lying in a very narrow (<15nm wide at the half-power mark) wavelength band. . Industrial SLM devices operate in the 380-420nm region because the emitters offer the best cost, power and curing performance of all the solid state devices. Additionally, the 380-420nm region offers advantages as that wavelength is especially safe and above the interference of many popular additives.

For reference, the output spectra of a medium pressure mercury lamp is shown below. This well recognized mercury, or “H” lamp footprint produced by all medium pressure lamps contains several well known peaks corresponding to the mercury spectra. These UV bands occur at 253nm, 312nm, and 365nm (the so called mercury “i-line”). The radiant emission in other peaks in the visible and the infrared region (not shown) detract from the curing ability of the source, for example, heat sensitive materials cannot be cured with mercury lamps unless the lamps have additional reflectors and filters installed.

Additives are often used to “dope” mercury lamps to produce spectral shifts at other wavelengths. The output of doped lamps depends on the specific additive used. The most common additives are iron (the “D” lamp) and Gallium (“V” lamps) though others also exist.

### A Language Barrier

At the top of the FAQ (frequently asked question) list for UV lamp makers is the popular question: “how much power does it have?” Our preoccupation with a simple measure to describe lamp power is like asking about the horsepower of a car engine. The answer can lead to problems. For example, a Shelby Series 1 and a Mitsubishi 3000GT both have identical horsepower (320 hp) engines. But the Shelby accelerates from 0-60 mph in just 4.4 seconds while the Mitsubishi takes 5.8 seconds. Is horsepower a good measure of going fast? If it were a locomotive would beat a Ferrari hands down on the drag strip.

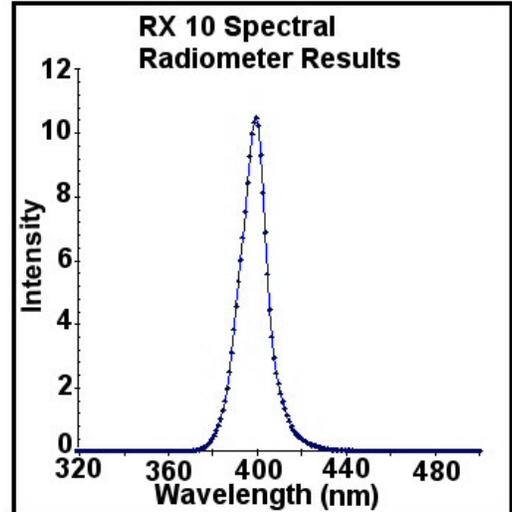


Figure 2. UV SLM Light Source Output

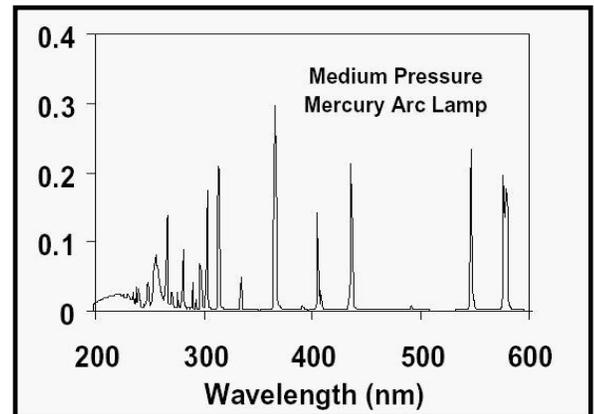
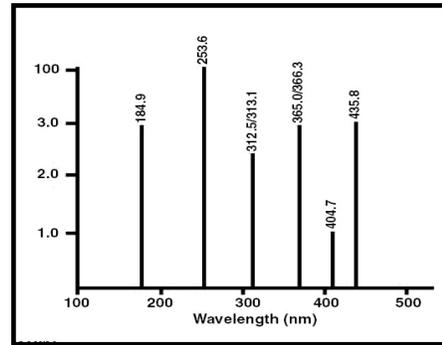


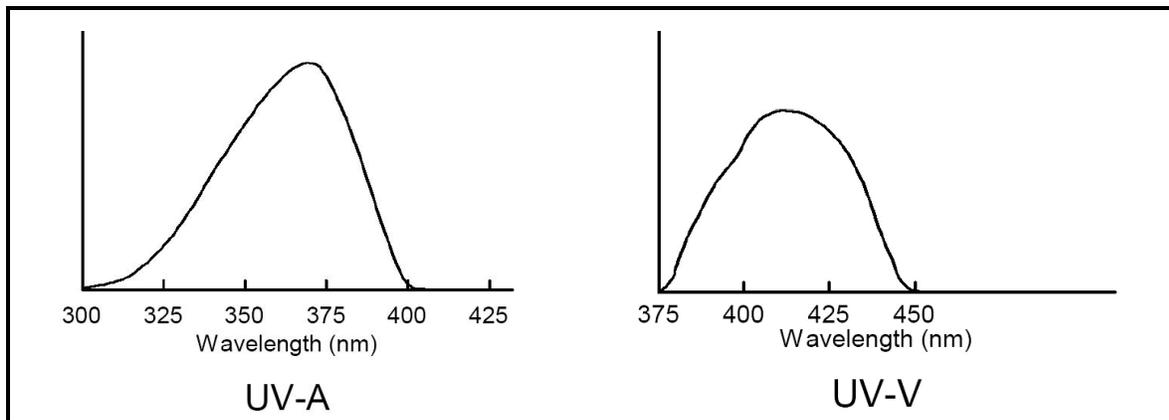
Figure 3. Mercury Arc Lamp Output

The problem of answering the “power” question is exaggerated by the fact that the tools used for this purpose (typically UV radiometers) have been developed to measure conventional mercury lamp sources. Shown here is the output spectrum for mercury that these devices are designed to measure.

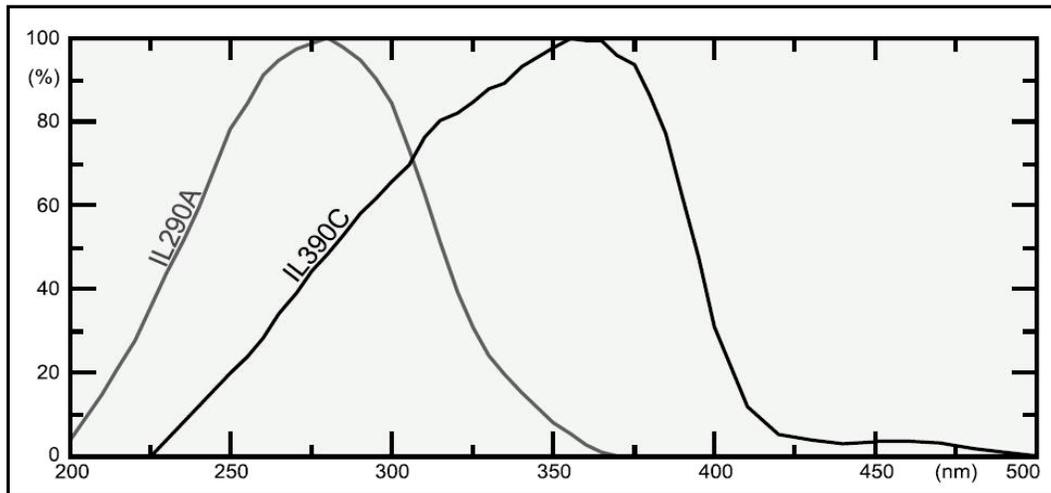


**Figure 4.** Typical Mercury Arc Lamp Output Wavelengths

The filter response curves shown below are used in some of the most popular radiometers sold for industrial applications (The International Light “LightBug” and the EIT “Power Puck”).



**Figure 5.** Radiometer filter response curves (Charts courtesy EIT, Inc.)



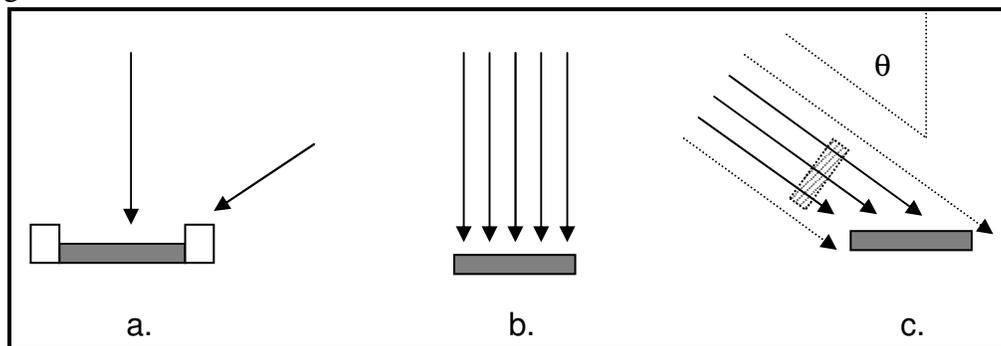
**Figure 6.** Radiometer filter response curves (Charts courtesy International Light, Inc.)

Neither of these excellent devices is ideally suited for measuring the output of narrow bandwidth semiconductor devices with a peak between 380 and 400nm.. The UV semiconductor devices emission falls into a valley in the filters that attenuates the readings at best.

Measuring output energy of UV light sources created with semiconductor devices with radiometers that were designed to work well with mercury lamps is a bit like listening to a dog whistle with human ears. We just are not hearing what they are – so it appears there is no sound. But a dog whistle is loud and clear to a pair of canine ears. To speak meaningfully about semiconductor device output we must create new tools and a new dialog that relate to narrow bandwidth energy.

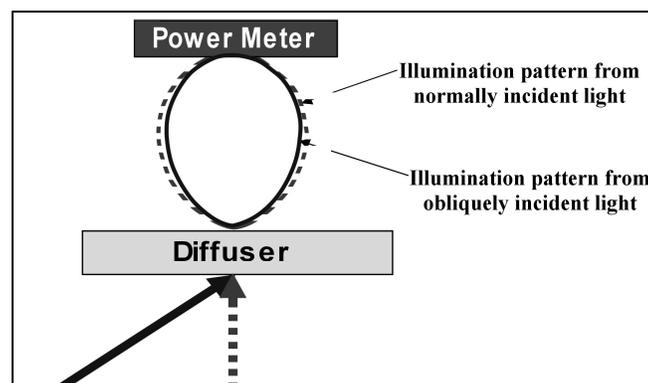
In addition, power meters are typically designed to collect light from only a relatively narrow range of incident angles. The physical geometry of the sensor itself may prevent the detector from “seeing” incident photons that do not project nearly straight in. As shown in Figure 6a, the sidewalls of the sensor housing may shadow the active sensor region and prevent photons with shallow angles of incidence from reaching the active region.

Area sensors suffer from cosine error – power density measurements of energy/area provide higher readings when the angle of incidence is close to 90 degrees than when the angle is shallower (illustrated in figure 6b and 6c). A non-orthogonal sensor behaves like a smaller sensor that is orthogonal to the incoming photons: the effective size of the non-orthogonal sensor is proportional to  $\cos \theta$ , where  $\theta$  is the difference between the normal to the sensor and the angle of incidence of the photons being measured.



**Figure 7:** Geometry of sensors can lead to underestimating incident optical power

One technique that solves this ray angle acceptance problem utilizes a diffuser placed between the illumination source and the sensor. As shown in Figure 7, a good diffuser (approximating an ideal diffuser) will create very similar patterns of illumination regardless of the incident angle of any incoming ray. This arrangement compensates for both the shadowing problem and for cosine error since all rays incident to the diffuser transmit equivalent illumination patterns to the power meter.



**Figure 8:** Operation of a diffuser.

As illustrated in Figure 8, when light strikes an ideal diffuser, the illumination pattern on the opposite side is independent of the angle of the incident light. In this example, incident normal light (90 degrees) creates an illumination pattern that is essentially the same as the illumination pattern created when highly oblique light strikes the diffuser (45 degrees).

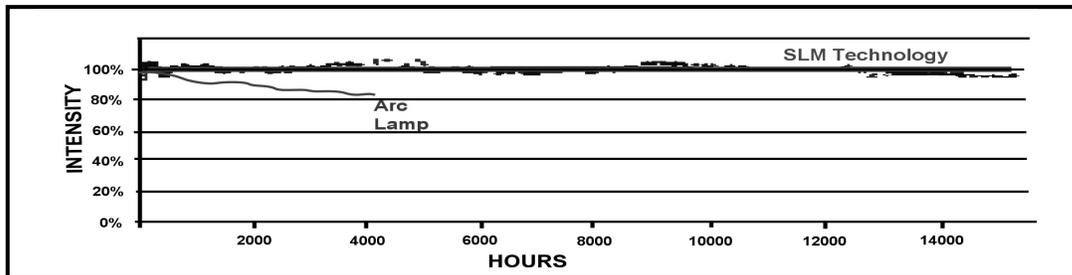
Although the total power measured by the detector will be less than the power reaching the diffuser at each point, both sources of angular bias will be removed and when calibrated correctly will produce accurate measurements. These measurements also reflect how materials cure, since most all formulations do not exhibit an acceptance angle.

## 2. Output Stability over Time

Solid-state UV emitters share the same characteristic we experience with other common semiconductor devices. That is, they seem to last forever.

Quantifying the lifetime of a UV source is a bit of a moving target. Conventional sources are typically specified to last from 1,000 to 8,000 production hours (depending on a wide range of factors). But usually the lamp energy is diminishing over time so that while the lamp is still operating it is producing less UV output than at startup. This degradation is affected by the number of on/off cycles, power, doping, ballast design, etc.

Solid state UV devices are not affected by these variables. The lifetime of UV SLM technology appears unaffected (in fact studies show that the lifetime may actually be enhanced) by turning the source on and off.



**Figure 9.** Output over time of Arc Lamps vs. SLM Technology

The accompanying graph is the actual measured output data for an UV SLM light source and an arc lamp sources. Note that the SLM light source has been running for over 14,000 hours without any noticeable sign of degradation.

While tiny individual emitters within the Semiconductor Light Matrix (SLM) may degrade or fail at different points in time, with proper design and construction the overall effect is negligible at the work surface. Solid-state devices appear to operate at, or near, their original output for their entire operating life, eliminating the need for frequent radiometric measurements or compensation measures.

### 3. Form Factor

UV semiconductor devices are constructed of nearly microscopic emitters arranged in an array. These arrays are not inherently limited in shape or size. In theory any shape of size semiconductor array can be constructed. A mile long light bar, a doughnut shaped source, or a source only millimeters across are all equally achievable. The limitation is the cost of manufacturing custom shapes compared to using standard modular shaped arrays.

These individual arrays may be positioned in any orientation and will produce uniform output. This flexibility and scalability of the technology allows SLM technology to be constructed for virtually any physical curing task without waste or inefficiency.

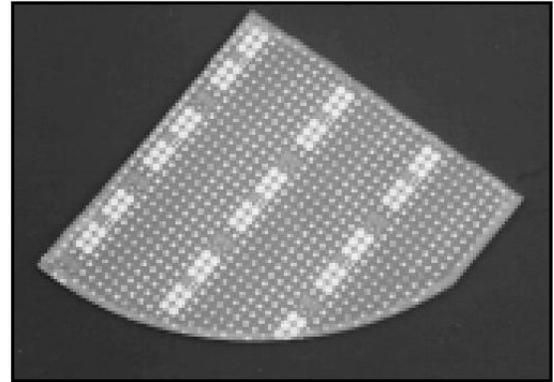


Figure 10. Raw semiconductor Devices

Semiconductor devices may be literally butted up against each other with virtually no edge effects. Using modular arrays, large surfaces can be irradiated “seamlessly” by multiple sources.

### 4. Surface Uniformity

A characteristic related to the combination of form factor and output consistency is the general 2-dimensional homogeneity of large SLM arrays. Results of uniformity measurements taken with a precision radiometric detector over a 25 x 89mm planar surface of the Phoseon RX 10 are shown below:

RX 10 25x89mm planar surface	Average Power (mW/cm <sup>2</sup> )	Standard Deviation	RAD (%) Standard Deviation/Average Power	(Max-Min) / (Max+Min)
Irradiance (through diffuser)	890	0.030	3.4%	0.081

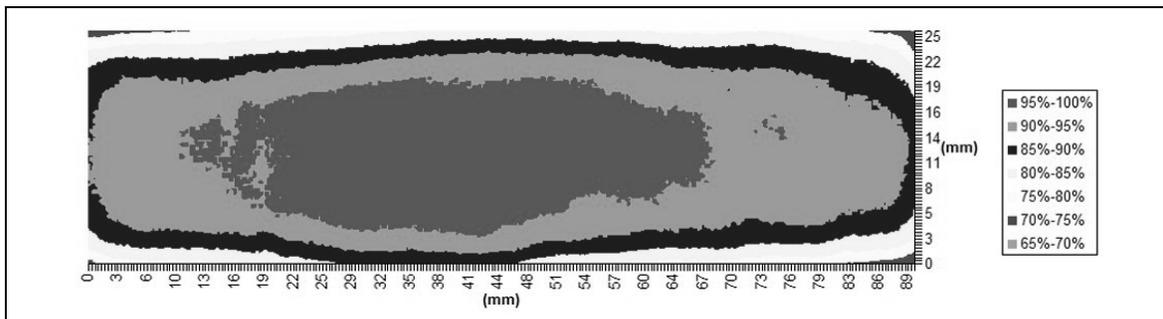


Figure 11: Digital Image of a Typical RX10 UV SLM Light Source

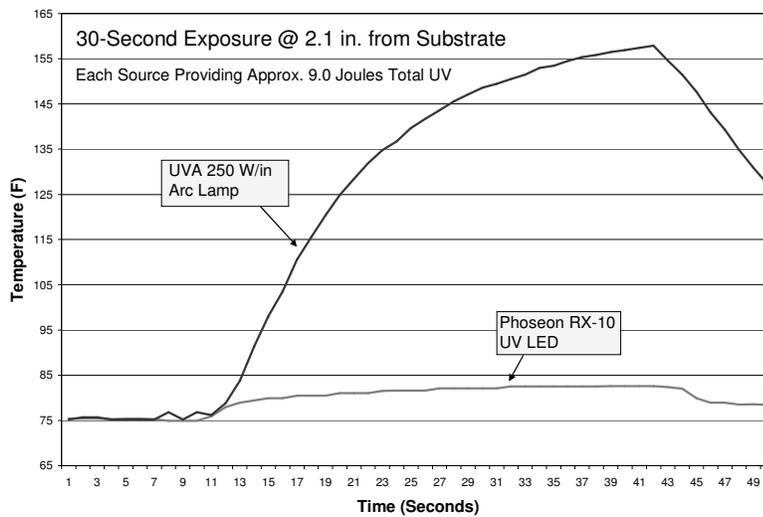
RX series products utilizing SLM technology typically have a performance of 2.0% RAD which corresponds to a 3 sigma confidence interval of +/- 60 mW at a 1000 mW/cm<sup>2</sup> average output.

The uniformity for the UV SLM is superior to the variations observed with arc lamp sources, which range between 10-20% RAD and results in a 3 sigma confidence interval of +/- 30 to 60%. In essence the sources have to be overdriven by a minimum of 15 to 30% to achieve reliable cure. This compounds the problem of inefficient coupling and long term stability.

## 5. Heat Generation

Semiconductor devices radiate a tiny fraction of the heat of conventional lamps. The heat that is generated at the surface mounting point of the semiconductor device itself is efficiently conducted out of the system. In fact no cooling air is required on the emitter surface at all. This makes SLM technology an ideal choice when it is important to maintain a regulated environment for contamination or low thermal impact on the material to be cured.

The following test results compare a 250W/inch UVA mercury lamp used in general industrial and automotive refinish applications with a UV SLM system positioned 2.1” from a temperature logging thermocouple. The relatively minor heat generated from the SLM technology after a continuous 30-second exposure is apparent even compared with the relatively low power UVA lamp where the radiated heat couples strongly into the work surface heating it rapidly. The heat generated by the UVA lamp (which continued to rise during the entire 30-second interval) reached temperatures unsuitable for many substances such as foils, paper, and many plastics.



**Figure 12.** Surface Temperature in Automotive Refinish Application of UV Lamp vs. SLM Technology

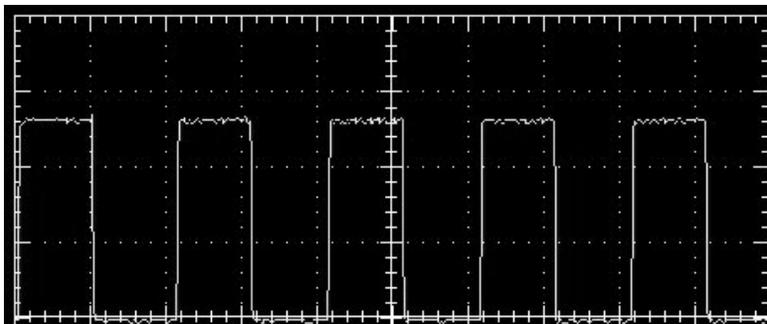
## 6. Rapid On/Off Capability

There is a good deal of common misunderstanding concerning the true “on/off” capability for UV sources.

Microwave lamps require nearly 20 seconds to cycle from 100% to zero to 100% again. However most of these microwave systems employ “standby” circuitry which allows the lamp to cycle from 100% to standby and back to 100% in just under 10 seconds.

If switched completely off, arc lamps could require over 15 minutes to restart and stabilize enough for use. The pressure buildup inside the lamp makes re-striking the arc more difficult until the internal atmosphere in the quartz tube returns to a low temperature (and pressure). However, shutters are commonly employed to block the escape of UV light mechanically. These shutters can be triggered in a fraction of a second, making them quicker in practice than even microwave sources.

By comparison, SLM technology cycles from zero to 100% in only 3 milliseconds. The near instantaneous cycling allows for immediate start and stop of UV energy, and may offer other advantages by pulsing or generating curing recipes to control curing characteristics of the formulation. The performance of the cured product can be adjusted by tight control of irradiance and dose.



**Figure 13.** Instant On/Off of SLM Technology

## Part II - Characterizing the Performance of UV SLM Technology

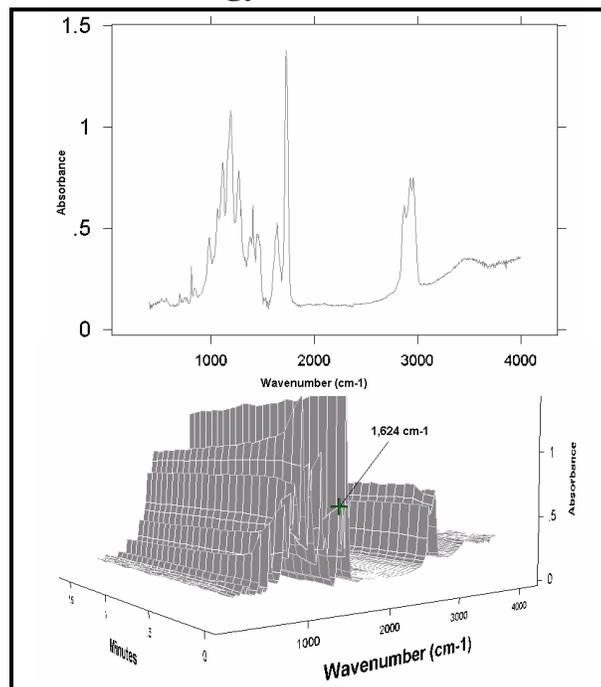
The “black box” SLM source has been described above, let’s now examine how its photons cure some common photo-chemistries.

A useful tool for studying the effectiveness of UV sources in curing applications is real-time infrared spectroscopy (RTIR). This technique allows in-situ measurement of the degree of cure as the sample is being irradiated.

The chemistry studied in the following examples has a C=C double bond in the original monomer which is visible at 1624 cm<sup>-1</sup>. As polymerization occurs, this bond is extinguished indicating the degree of polymerization. The narrow 1624 spectral band can be isolated and the relative absorbance of IR energy observed which is directly correlated to degree of cure.

Samples were exposed to both a traditional mercury based source (a LESCO MKII spot cure source) and to a UV SLM technology source (Phoseon RX Firefly) unit for an exposure period of 60-seconds.

The sources were located approximately 1.75” (45mm) from the target cell to give near equivalent curing setups and intensities. The following radiometric data was recorded with an EIT 4-channel Power Puck. (Note the discussion above however on comparison of the measurements).



**Figure 14.** C=C double bond at 1624nm



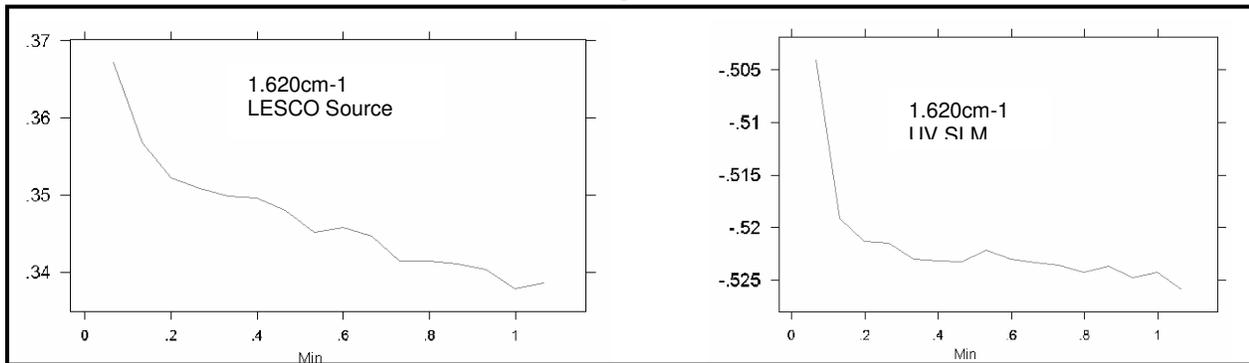
**Figure 15.** RX Firefly UV SLM Handheld Product

	Hg Source Peak Irradiance mW/cm <sup>2</sup>	Hg Source Dose J/cm <sup>2</sup>	SLM Source Peak Irradiance mW/cm <sup>2</sup>	SLM Source Dose J/cm <sup>2</sup>
UV-A	72.1	3.221	8.1	0.255
UV-B	27.3	1.110	0.0	0.0
UV-V	52.5	1.988	102.3	5.521

**Table 1:** Comparison of Radiant Output for Lesco MKII and RX Firefly

It is interesting to note that both devices produce roughly the same amount of UV power (a bit over 5 Joules), but the energy is distributed much differently over the UV-A, UV-B, and UV-V bands.

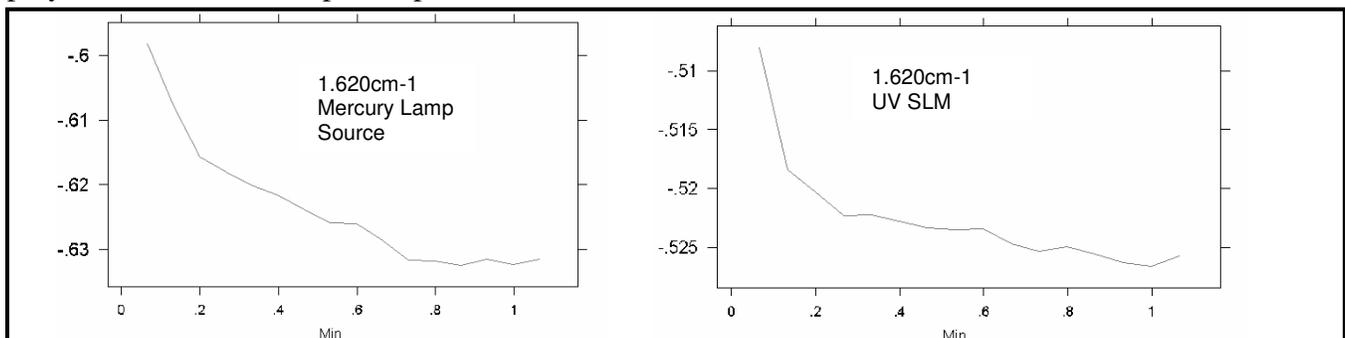
Two experiments were conducted. The first sample is a free-radical cure, black inkjet ink that has been formulated to work well with UV Curing.



**Figure 16.** Speed of cure with Arc Lamp vs. SLM Technology of Inkjet Ink

As the graphs indicate, the ink cures rapidly (< 10 seconds) with SLM technology but requires a full 60-second exposure with the spot cure mercury source. This is due to the much more effective coupling of the energy into the polymerization reaction. In the case of the mercury lamp source the radiation is not driving the reaction. The SLM light source effectively cures 6 times faster with the same intensity. (Industrially this ink can be cured in fractions of this time with a more powerful SLM source and closer target distance. The test cell does not permit simulation of a production environment however.)

The second test sample is a commercial clear UV topcoat used for scratch-resistant coatings on polycarbonate and other plastic parts.



**Figure 17.** Speed of cure with Arc Lamp vs. SLM Technology of Clear Coat

As illustrated in Figure 17, where the chemistry has not been intentionally tuned to the wavelengths for SLM technology, the coating does cure, but not as efficiently as the same coating cured with a conventional UV source.

In summary, the results of field trials show that materials optimized for UV SLM technology not only cured 6x faster, but cured with better results than using a conventional UV lamp. Although, non-optimized materials cure, they cure at a 20% slower rate.

### Part III. Looking Ahead: Building a New Toolbox

UV semiconductors have garnered a great deal of interest owing to some of their attractive characteristics (such as low energy consumption, long lifetime, low heat generation, output stability, no mercury, and high uniformity among others).

These devices have markedly different output spectra than conventional UV sources. Even to an untrained eye, the narrow spectral output of a semiconductor device does not resemble the broad output of a Fusion lamp commonly used in industrial applications. Make the scale and the boldness of the SLM line much more obvious.

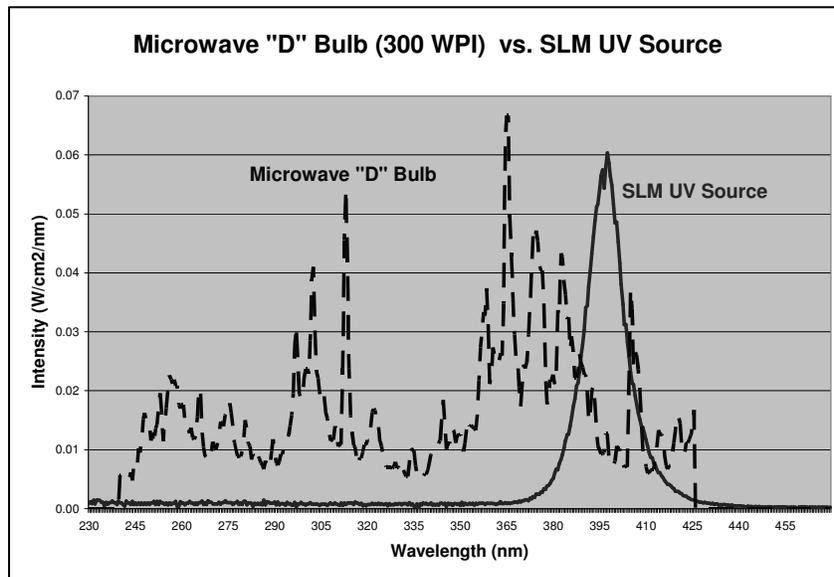
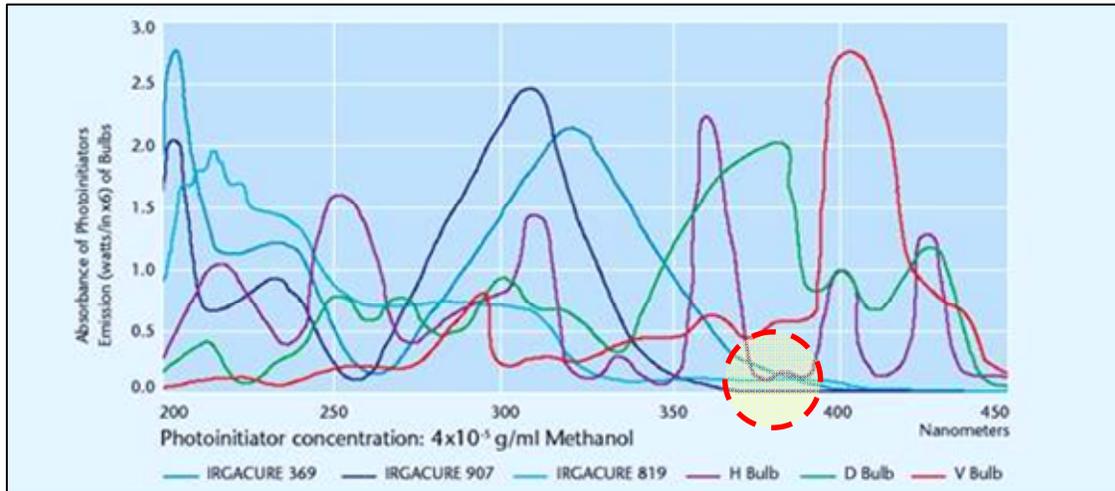


Figure 18. Spectral output of Fusion Lamp vs. SLM Technology

Not surprisingly, the suppliers of photo-reactive chemicals have responded over the last few decades by developing photoinitiators that react well to the light sources popular for UV curing. Their commercial sales literature ties together their chemistry and the popular lamps.

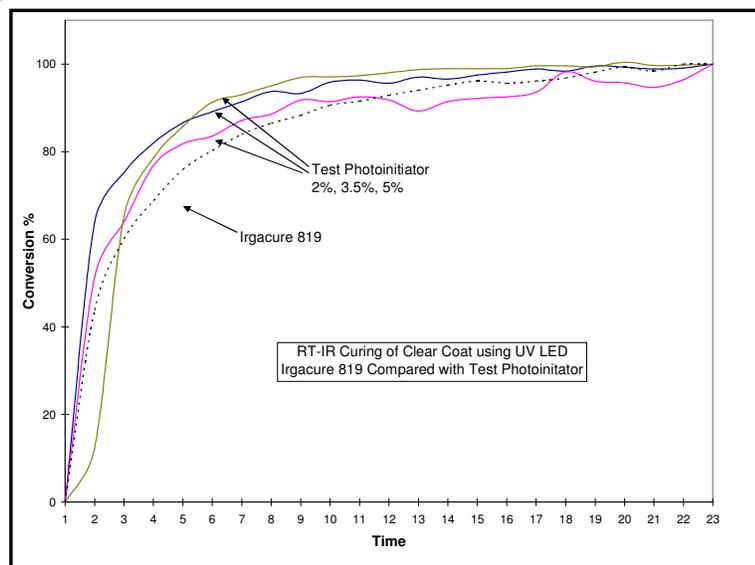


**Figure 19.** Photoinitiator absorption curves (Courtesy Ciba Specialty Chemicals Corp.)

While these chemistries usually work with solid state sources, they were not developed, and are not ideal for them. By a more thoughtful selection much better results are obtained.

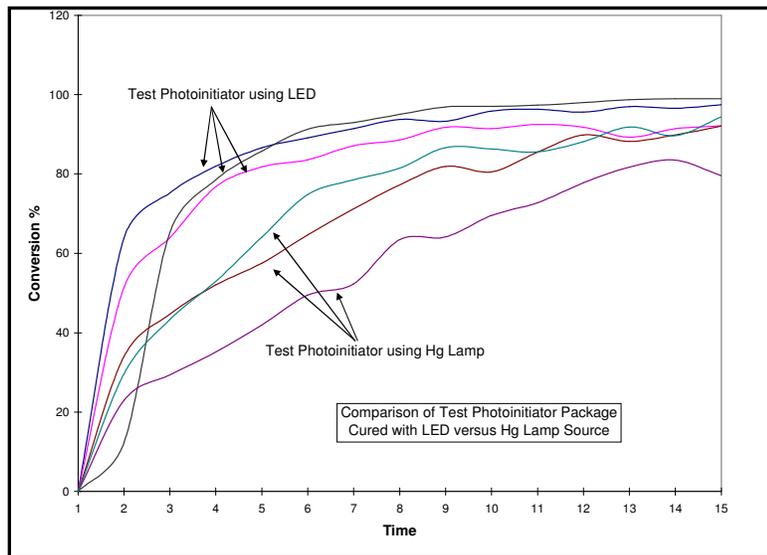
For example, recent field trials in the wood coatings applications revealed that adding even a small percentage of a second photoinitiator (TPO) suited to 380-420nm light to a commercial formulation containing Ciba Irgacure 819 (BAPO) had a significant and positive effect on the rate of cure and surface properties.

Our recent work has been to identify photochemistry packages which are more optimally matched to the SLM source. In the example below, a new selection of photoinitiator not commonly used for UV curing was tested.



**Figure 20.** RT-IR Clear Coat cured with SLM Technology UV source using Test Photoinitiator

The new package is more suited to the 380-420nm SLM source than a typical Hg lamp photoinitiator like Ciba Irgacure 819.



**Figure 21.** RT-IR SLM Technology UV source vs Arc Lamp using Test Photoinitiator

A traditional mercury lamp UV source does not perform as well using this same photochemistry, showing that the real opportunity for the future is to significantly improve UV curing by optimizing formulations to solid state light sources. If done properly, curing rates 5-20 times faster than is possible with existing lamp sources is achievable. This will revolutionize the UV curing industry and result in achieving the actual benefits of solid state technology. These benefits include lower costs for production, less environmental impact in production as well as disposal, faster throughput and better factory utilization along with a superior process control impossible to achieve with conventional UV sources.

Work is now underway to categorize what chemistry works well with these new sources to aid formulators and to develop successful applications. Work is also underway to develop new cure mechanisms and photo-reactive chemicals that are optimized for these devices in the same way that the previous generation of lamps and chemistry were developed. The author invites those interested in participating in this progress to contact us for additional information.

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**Acknowledgements:**

The authors wish to thank the great support and assistance of the team at Phoseon Technology; Mark Owen, Jon Marson, Tom Molamphy and especially Bonnie Larson We are also indebted to the team at the University of Akron for their ongoing assistance with our real-time IR studies; Dr. Mark Soucek, Dr. Hua Gu and Kosin Wutticharoenwong and to our colleagues at Kalcor Coatings, Tim Hlabse and Eileen Adams for aid in coating formulations for the real time IR studies.