Investigation of light output uniformity and performance using a UV transmitting glass optic to improve cure quality

Brian Jasenak, Rachel Willsey, Adam Willsey, James Forish

Kopp Glass
2108 Palmer Street
Pittsburgh, PA 15218

ABSTRACT

Ultraviolet light-emitting diode (UV LED) adoption is accelerating; they are being used in new applications such as UV curing, germicidal irradiation, nondestructive testing, and forensic analysis. In many of these applications, it is critically important to produce a uniform light distribution and consistent surface irradiance.

Flat panes of fused quartz, silica, or glass are commonly used to cover and protect multi-UV LED arrays. However, they don’t offer the advantages of an optical lens design. An investigation was conducted to determine the effect of a secondary glass optic on the uniformity of the light distribution and irradiance. Glass optics capable of transmitting UV-A, UV-B, and UV-C wavelengths can improve light distribution and intensity.

In this study, a UV transmitting glass formulation and secondary linear optic were designed and manufactured to demonstrate their effects on achievable irradiance intensity and uniformity. Prismatic patterning on the light source surface of the lens was used to minimize reflection losses on the incident surface of the glass. Fresnel optics were molded into the opposite side of the UV transmitting glass to control the refraction of the light and to gain the desired light intensity distribution from two multi-UV LED arrays. A 20% increase in relative irradiance was observed while maintaining the same coverage area. This work discusses the optical design and the resulting benefits of controlled light output on UV LED systems, which include reduced driving current, decreased thermal deterioration, improved energy efficiency, and longer LED lifetime.

Keywords: UV, Ultraviolet, UV LED, Optics, Glass, UV LED Optics, UV Transmitting Glass, UV Optics, UV Curing, UV Germicidal Irradiation

1. INTRODUCTION

The industrial curing and germicidal irradiation markets are rapidly evolving with the introduction of ultraviolet light emitting diodes (UV LEDs). They offer many benefits compared to mercury vapor and other similar UV light sources, including lower maintenance costs, greater reliability, low heat, increased power control, and, of course, efficiency savings. However, high costs, formulation compatibility, irradiance uniformity, and working distance constraints are challenges that still limit their widespread adoption into new UV markets.

Due to the common practice of using multiple LEDs in an array and the directional nature of their light output, irradiance non-uniformity can occur when the spacing between LEDs in the array causes irregular energy distributions on the incident light surface. Flat windows of fused quartz, fused silica, or glass are commonly used to cover and protect multi-UV LED arrays within UV LED curing or germicidal irradiation systems. These covers provide no optical influence and only provide protection. As a result, the irradiance pattern on the incident surface can be non-uniform.

In this study, a proprietary UV transmitting glass composition and secondary optic were designed and manufactured to demonstrate their effect on achievable irradiance intensity and uniformity. Prismatic patterning on the light source surface of the optic was used to minimize reflection losses on the incident surface of the glass. Fresnel optics were molded into the opposite side of the UVA transmitting glass to control the refraction of the light and to gain the desired light intensity distribution. The optic was used with two different UV LED arrays.

This paper discusses the optical design, glass selection, and the resulting benefits of controlled light output on UV LED curing systems, which include reduced drive current, improved energy efficiency, improved thermal management, and longer LED lifetime. Additionally, the benefits from the experiment outlined in this paper can be applied to UVC applications, such as UV germicidal irradiation.

2. EXPERIMENT

2.1 Irradiance non-uniformity in UV LED cure systems

When using UV LED curing systems, uneven curing can occur when there is a non-uniform irradiance pattern on the cure surface. Similarly, disinfection systems are less effective when the energy distributions is non-uniform. This is due to both the directional nature of UV LEDs and a non-optimized array design, which can produce an irradiance pattern that has areas with higher irradiance measurements.

Unlike conventional light sources, which are typically omnidirectional, LEDs emit light in a directional nature. In addition, LEDs produce a spectral power distribution with one peak wavelength rather than multiple peaks, as in mercury vapor lamps and other UV emitting light sources.

For UV LED adoption to accelerate in large-format industrial curing, wide flexographic printing markets, and disinfection applications, uniformity and irradiance improvements will be needed to improve light quality distribution. This study aims to develop a solution that increases irradiance and improves irradiance uniformity and quality.

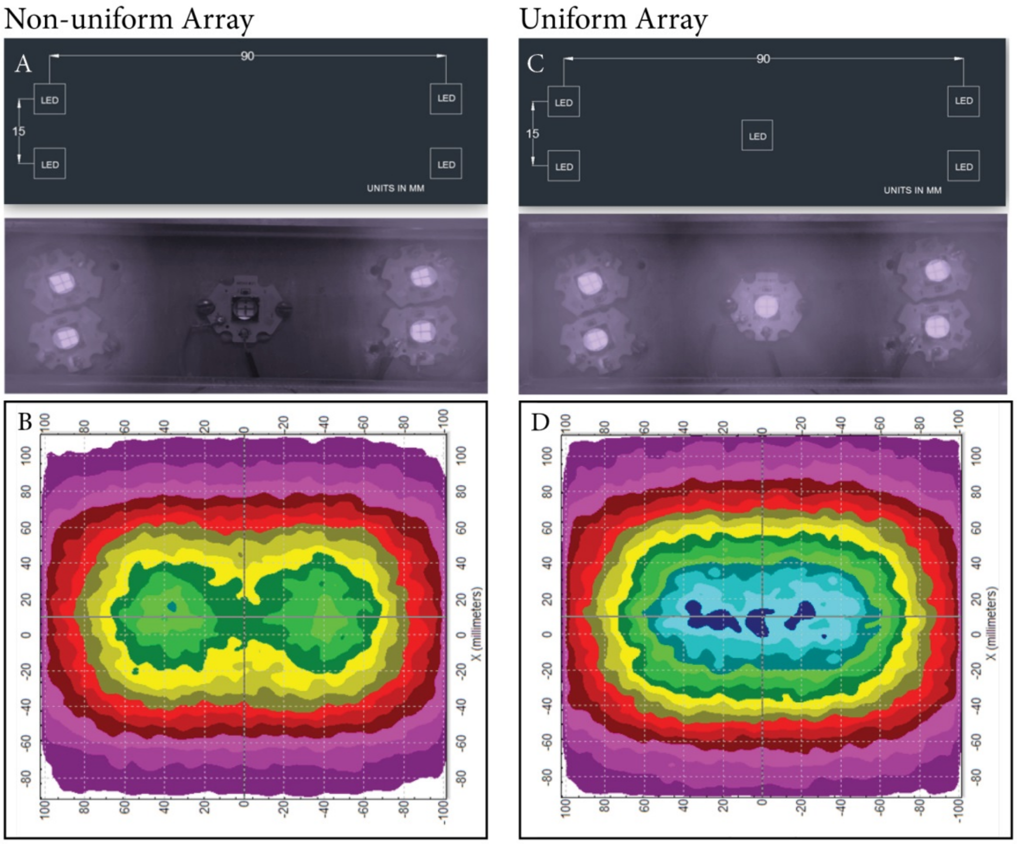


Figure 1. The (A) array designed to produce drastic irradiance non-uniformity; pictured below is the (B) simulation of the irradiance pattern. Pictured on the top right (C) is the array designed to produce a relatively uniform irradiance pattern; pictured below is the (D) simulation of the irradiance pattern.

2.2 UV LED array construction and light distribution simulation

Two LED arrays were designed to simulate two different UV curing systems, pictured in Figure 1A and 1C. One system used four UV LEDs and was designed to produce drastic irradiance non-uniformity. The other system used an additional LED and produced a more uniform light distribution. The arrays were simulated using TracePro to demonstrate the desired light distribution patterns (Figure 1B and 1D).

2.3 UV optic design (patent pending)

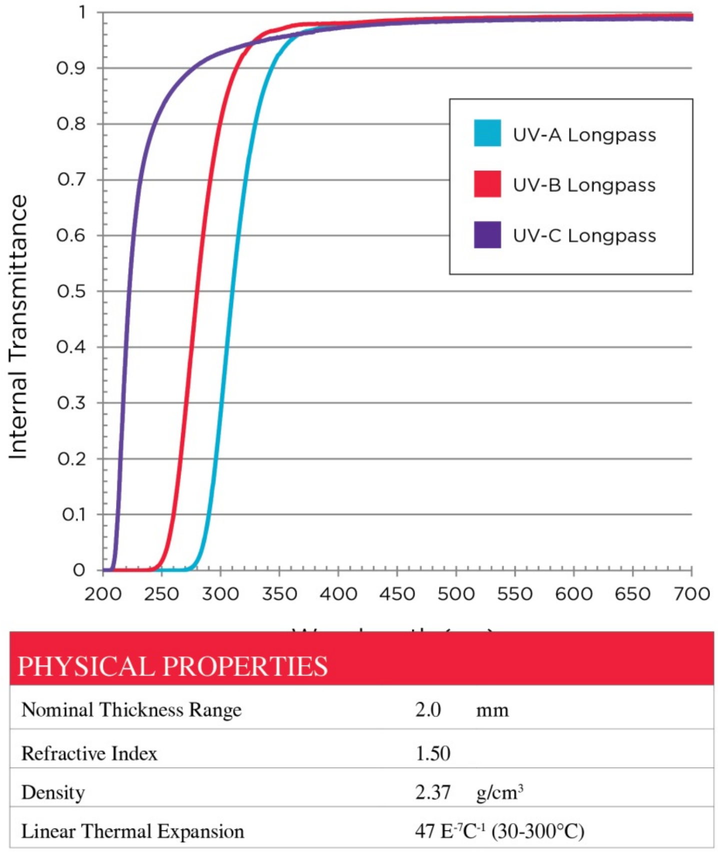
A secondary linear optic was designed and manufactured to demonstrate its effect on achievable irradiance intensity and uniformity. Prismatic patterning on the light source surface of the optic was used to both minimize reflection losses on the incident surface of the glass and to scatter some of the intensity in the high irradiance areas. Fresnel optics were molded into the opposite side of the UV transmitting glass to control the refraction of the light, to re-focus the light onto the target surface, and to gain the desired light intensity distribution from two UV LED arrays.

2.4 Working parameters, components, and measurement tools

In this study, arrays were designed with LED Engin LZ4 UV LEDs with a 395 nm peak wavelength. Measurements were taken in 0.5 inch increments over a 5x8 inch surface area. The LEDs were positioned above the measurement surface at a working distance of 1.5 inches. A T10 Minolta illuminance meter was used for relative irradiance/illuminance measurements on the incident surface during the study.

2.5 UV glass composition: optical and physical properties

Three proprietary glass compositions (Figure 2) were developed that have high transmission across the UV and visible spectrum. For the experiment, the UV-A glass composition highlighted in blue in the plot below was use for the optic material. Transmission at 365 nm is 92% and was comparable to fused quartz and silica.



PHYSICAL PROPERTIES		
Nominal Thickness Range	2.0	mm
Refractive Index	1.50	
Density	2.37	g/cm^3
Linear Thermal Expansion	47 E^{-7}C^{-1} (30-300°C)	

Figure 2. Optical and physical properties of the UV transmitting glass composition developed to create the UV optic.

3. RESULTS AND DISCUSSION

3.1 Array Measurements: irradiance non-uniformity improvements

3.1.1 Non-uniform array with flat window cover

The non-uniform array with a flat window cover produced an irradiance pattern with two high output areas. These areas produced a general relative irradiance of .8 to 1.0 or 80% to 100% of the irradiance produced by the array. There was a noticeable gap between the irradiance peaks where the relative irradiance drops to between 60% and 80%.

Specific to UV curing and considering a worst case scenario, two areas on the same cure surface which need the same energy density (Joules/cm$^{\wedge 2}$), or irradiances per second (Watts/Second/cm$^{\wedge 2}$), to be cured can be compared. One part of the cure surface was illuminated by an irradiance peak, 100% irradiance, and another part was illuminated by the gap between the irradiance peaks with 60% irradiance. Assume all other factors are constant; the area under the 60% irradiance would not be cured completely because the line speed of the curing was set for 100% irradiance. If the 60% to 100% irradiance is compared in terms of line speed, the area with a decrease in irradiance would require 67% more time to cure. Therefore, it would not cure completely under the 100% irradiance conditions. If the line speed was changed to accommodate for the 60% irradiance then, the high irradiance areas could over cure and present quality issues.

Similarly, negative effects of non-uniform light distribution can be seen with germicidal irradiation applications. Inconsistencies, in the irradiance, could cause varying levels of irradation on the same surface causing some areas to become sterilized while other areas do not have sufficient time for sterilization. The need for uniform surface irradiation and sterilization is critical for germicidal applications.

3.1.2 Non-uniform array with UV optic

A linear Fresnel UV optic was designed and used to minimize the non-uniformity seen in Figure 3A. The linear Fresnel UV optic was enhanced with specific diffusion patterns on the back of the optic that minimized reflection losses on the incident surface of the glass.

The resulting relative irradiance pattern is depicted in Figure 3B. Notice the non-uniform irradiance pattern has been nearly eliminated with the addition of an optic. The peak irradiance across from each LED pairing maintains a relative irradiance above 95% from peak to peak. Additionally, there is a sudden and consistent decline in irradiance when moving away from the irradiance peak.

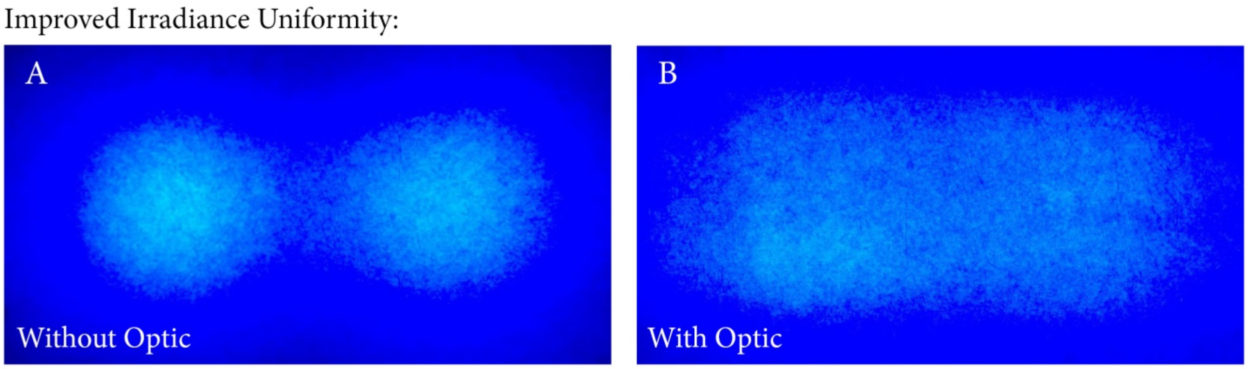


Figure 3. Pictured on the left (A) is the irradiance pattern produced by the non-uniform array without an optic. On the right (B), the irradiance pattern that is produced when an optic is added. The optic increased irradiance by 30% between the two peaks.

3.2 Array measurements: irradiance improvements

A UV LED array that does not experience irradiance uniformity issues can still be optimized with the addition of an optical lens. Most UV LED applications use arrays paired with flat glass or quartz window covers; this cover can be replaced with a thin (3-6 mm thick) secondary optic.

Consider the uniform distribution array depicted in the simulations (Figure 1D). The actual irradiance pattern is depicted in Figure 4A and would be acceptable for most UV curing or germicidal disinfection applications. It has a relatively consistent distribution and increases steadily to the peak of the map.

The uniform array consisted of five LED Engin LZ4 395nm LEDs, which ran at 700mA. If this array was covered by a traditional flat glass or quartz window, there would be an opportunity to improve the whole LED system. By replacing the flat window with the linear Fresnel UV optic discussed in the previous example, the irradiance could be increased to a peak value near 120% of the irradiance produced by the array with the flat window cover (Figure 4B).

This irradiance increase allows for two possible improvements to the LED system; the line speed could be increased, or the input current could be decreased. Much like the previous example, increasing the line speed is possible because of the increased irradiance. Less time is required beneath the LEDs because more energy can be focused onto the cure or disinfection surface. Some overlooked benefits are the effects the irradiance increase can have on the LEDs. With the optic applied, there was an increase of almost 20%. This increase enables numerous benefits to the UV LED system, including reduced power consumption and thermal management requirements, increased working distances, and potentially longer LED lifetimes. These benefits and their impact to the UV LED system are discussed in the next section.

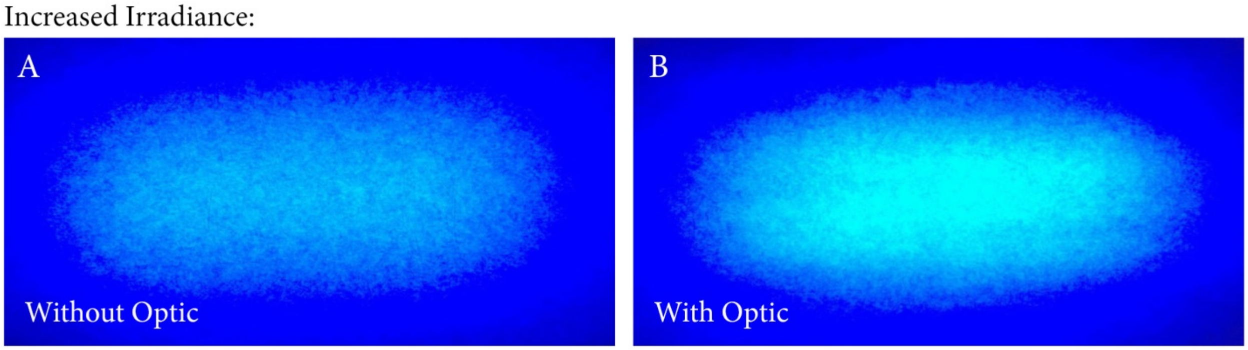


Figure 4. Pictured on the left (A) is the irradiance pattern produced by the uniform array without an optic. On the right (B), the irradiance pattern that is produced when an optic is added to a uniform array. The optic increased irradiance by 20%.

4. CONCLUSION: IMPACT OF THE UV OPTIC

As demonstrated, the use of a UV optic can increase irradiance and produce a more uniform light distribution; this has numerous benefits on the UV LED system and on the UV curing system as a whole.

4.1 Impact on UV LED lights

4.1.1 Reduced power consumption and better energy efficiency

The LEDs used in this study's array have an input power of 700 mA and generate nearly 10W. It can be calculated that by under driving the UV LEDs in this array by 1W, the same irradiance output can be achieved if a UV optic is used. The level at which the LEDs can be under driven can be enhanced by optimizing the UV optic for the array.

4.1.2 Higher-performing lights with fewer UV LEDs

When first transitioning to UV LEDs one of the biggest barriers to overcome is their high cost. In high-performance flood curing units, it's essential to maximize irradiance uniformity over large areas, which often requires large numbers of UV LEDs.

A UV optic reduces the initial LED investment required; optics increase irradiance and permit the use of fewer UV LEDs in the unit while still achieving the desired energy density.

4.1.3 Reduced thermal management requirements and extended UV LED useful life

The key to increasing the useful life of a UV LED is proper thermal management. In high-energy applications, UV LEDs require rapid heat extraction; otherwise, an increase in junction temperature will lower the luminous flux and cause the UV LED to degrade more quickly.

The use of an optic enables the reduction of the number of UV LEDs required in the array or enables a reduction of the drive current to the UV LEDs. Both of these options produce the desired light intensity while reducing the thermal management requirements.

As mentioned above, the use of an optic could allow the array to be under driven by at least 1W. A lower current produces less heat that needs to be dissipated. As a result, this increases the effectiveness of the LED system components and can help increase the lifetime of the LED.

4.1.4 Minimized peak wavelength shifts

Excess temperature can cause LED components to break down over time; the metal junctions and the semiconductor material of an LED can deteriorate, and as a result, the luminous flux of an LED will decrease, and the peak wavelength (color) can shift.

The LED Engin LZ4 UV LEDs can approach a 5 nm shift when operated at temperatures near 100 °C. By under driving the LEDs slightly, the strain on the LED components can be reduced and as a result, this decreases the opportunity for color shifting, which can cause issues in the production and quality of UV cured applications or sterilization times and effectiveness.

4.2 Impact on UV LED curing systems

4.2.1 Increased working distances and curing of 3D forms

Molded UV glass optics increase the energy density hitting the cure surface and enable greater flexibility in cure system working distances. Maximizing irradiance with optics allows the curing of complex 3D surfaces and ensure that the light is evenly distributed onto the surface.

4.2.2 Improve productivity and cure quality

LEDs inherently increase the productivity of UV curing operations; they aren’t as variable as mercury vapor lamps, have greater reliability and lifetime, and require less maintenance.

An increase in irradiance can boost the performance of the entire curing operation even more. With greater energy density reaching the surface, line speeds can be increased and processing times shortened. UV optics improve irradiance uniformity and ensure that even at faster speeds, the system can still produce a uniform cure.

4.3 Impact on UV LED irradiation systems

4.3.1 Improved light control for sterilization

To overcome UVC LED challenges such as lower power, high cost, minimal effective distance from fixture to target surface, and non-uniformity similar linear optics can be used to improve light distribution.

Similar to UV curing applications, increased energy and uniformity on the disinfection surface helps resolve concerns regarding UVC LED efficiency and power output. Optics provide light distribution control, as the UVA experiment shows, which directly affect junction temperature and lifetime. Ray trace simulations have shown promising results similar to the UVA LED experiment. Therefore, it is concluded that the benefits of optics on UV curing systems in the UVA region can also be seen in applications like germicidal irradiation when an optic is paired with UVC LEDs.