UV LED Lens Technology

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Abstract

High power, large area LED arrays tend to be distributed light sources with Lambertian emission patterns. Therefore, compared to traditional mercury bulb UV light sources, UV LEDs need new and innovative optical design strategies to control and deliver light to the materials being processed. We present quantitative improvements in practical working distance and optical power densities for UV LED arrays using advanced lens designs.

Introduction

Ultra Violet Light Emitting Diodes (LEDs) are attractive for many materials processing and inspection applications. LEDs are a solid state light source that have a narrow optical spectrum, are energy efficient, rugged and reliable. In addition, UV LEDs can be built into environmentally friendly mercury free, lead free and RoHS compliant light sources. The performance of LEDs is following a Moore's law like growth with output power rapidly increasing bringing new applications within the reach of LED equipment. However, the optical and other physical properties of LEDs are significantly different from traditional mercury light sources. Therefore, careful consideration of these differences will influence the optical design and use of UV LED systems. This paper investigates various strategies for designing optical systems for LEDs and makes comparisons with the optical design of traditional mercury lamp systems.

Outline

This paper first reviews the physical characteristics of UV LEDs that influence the optical design of these systems. These constraints are compared with the incumbent mercury bulb technologies. Then the paper focuses on the influence of using arrays of LEDs on their optical design. This is followed by discussions on optical loss mechanisms, edge effects for finite arrays and beam pointing systems. The results of an array of 18 LEDs emitting at 365 nm with various lens solutions is presented followed by a summary.

LED Characteristics

The geometry of LED devices and their fundamental physical requirements influence the design of their optical delivery system. The primary requirements are input electrical power, light extraction, waste heat removal and mechanical support. These requirements are shown schematically in Figure 1. Electrical power is delivered to the active LED through metal traces and wire bonds, while heat is drawn away from the LED by a solid substrate to be transferred to the ambient air or a liquid coolant. Effective thermal management is important since high temperatures decrease the LED electrical to optical conversion efficiency and shortens the device life. It is generally desired that the substrate provides mechanical support as well as good thermal conductivity, so it is often constructed from opaque metal or ceramic materials. As a result, the emission pattern from a single LED typically spans a hemispherical arc.

Unlike lasers, LEDs are spontaneous emission devices, so the spatial emission pattern is in all directions. The light pattern is Lambertian, implying a wide angle distribution. This Lambertian characteristic is modified by the allowed escape angles of light from the high index of refraction of the semiconductor material to the low index encapsulant or air. In practice most encapsulants are damaged by prolonged exposure to high intensity ultraviolet radiation, so many shorter wavelength LEDs do not benefit from the use of index matching encapsulating materials to increase light extraction. In addition, the pattern is further constrained by the mechanical and thermally conductive support. Two examples of the resulting light pattern are shown in Figure 2. The emission patterns show additional shoulders due to the fact that the dominant emission region of the LED is a flat surface, rather than a three dimensional sphere.

Most high power LEDs are designed to benefit from the transparent substrate materials in the growth of the LED. The light that reflects from the bottom of the LED is effectively redirected to the front emission pattern by using a reflective contact material. Many designs also incorporate reflectors around the active LED chip to help redirect edge emitted light upwards. Some leading edge commercially available UV LEDs now incorporate nano structures or photonic crystals into the LED chip to enhance light extraction and reduce the emission angle from the LED die.

Mercury Bulb Characteristics

The traditional ultra violet light source is an electrically driven mercury plasma contained in a quartz enclosure. Optically, the light emission region may often be treated as a line source in the case of a discharge tube or a point source in the case of a short arc lamp. These two configurations can be thought of as a two or three dimensional version of a point source. For linear configurations, the light source is continuous as the driving electrical current flows down the tube. The mercury plasma is at a very high temperature which is typically contained by a UV transparent quartz vessel. The light emitted from the excited mercury plasma is in 360 degrees, so a parabolic reflector is often used on the back side of the tube to direct all the light forward. The back reflector plays a role similar to the reflective mounting contact of an LED.

LEDs in Arrays

Generally, large LED light sources are composed of an array of light emitting components rather than a single, large continuous device. There are several reasons for assembling LED light sources into arrays. First, the semiconductor manufacturing processes used to produce LEDs do not lend themselves to making active areas larger than a few square millimeters. Typically, LEDs are fabricated using wafers tens to hundreds of millimeters in diameter. The size of the LED die is much smaller than the size of the wafer to increase the process yield. An LED die the size of a wafer would become a total loss if the wafer includes a single fatal defect. Therefore, the wafer is partitioned into many much smaller die that are individually tested and screened. With the smaller die, only the die that contain the fatal defect are discarded while the remaining smaller chips can be used.

Second, thermal management issues also limit the practical device size. Typically, there is a mismatch in the thermal expansion coefficient of the LED material and the heat sink materials that provide support. As the die temperature increases from ambient to operating temperature, the thermal expansion mismatch creates strains in the chip that could lead to fracture and device failure. With smaller die, the total magnitude of the expansion mismatch is limited and stress related failures are avoided.

Third, the extraction of waste heat is necessary to maintain a low LED operating temperature with high electrical to optical conversion efficiency. Spreading out the active LED chips into an array of discrete chips distributes the heat sources easing the demand on air or liquid cooling.

Working Distance-Lenses

For many applications, the working distance from the light source to the illuminated target is a practical consideration. For instance, to illuminate a three dimensional object traveling down a conveyor, it might be necessary to position the light source away from the surface of the conveyor. It might also be necessary for a camera to have an unobstructed view of the target being illuminated for inspection purposes. In these cases, a lens system that would maintain the optical power over an extended distance is helpful. A single lens can be used if the light source is a single point, or line. However, for an extended two dimensional array of LEDs, a single lens has some limitations. When a single large lens is used to re-image an array of LEDs, the array pattern is recreated on the material being illuminated. For many applications, this pattern of discrete LEDs on the material being processed may result in non uniform processing. Therefore, an array of lenses can offer an attractive solution.

Gradually Expanding Beams

Figure 3 is a sketch of an array with four LEDs and four lenses to illustrate some of the basic principles of gradually expanding beams. Because the lenses confine the radiation from the LEDs, the irradiance (power/area) from the array is higher than the case without the lens array. The far field angular distribution of the power is also a critical issue for many processes such as processing photo resists where a particular profile is desired. The lens system studied produced a 6.5 degree half angle. This value was calculated from the measured working distance and image size of the chip. A consequence of the narrowly confined beam is the gaps in the optical pattern at position "A" for distances less than "L" in Figure 3. The distance L where the gaps are filled in can be calculated by $L = d/(2 \tan(\theta))$. In this equation, d is the distance between the LEDs and θ is the half angle of divergence of the beam. If perfectly collimated beams were created, they would not be able to fill in the open spaces between the lenses.

The benefit of using a gradually expanding or partially collimated beam is illustrated when comparing Figures 4A and 4B. Each diagram shows a schematic of the optical design along with a photograph of the irradiation pattern transmitted through a projection screen with a 1 cm x 1 cm grid. The measured irradiances for LEDs emitting at 365nm were for a working distance of 7.5 cm which is approximately the distance "L" where the adjacent beams overlap. Within the illuminated region using the gradually expanding beams (4B), the irradiance is 7 times higher than the case without the lens array. The results can also be seen in Figure 5 which plots the irradiance level as a function of working distance. The difference in the irradiance is quite dramatic when comparing the results with the gradually expanding beam lenses (line with closed boxes) with the same LED head without lenses (line with "x".)

Insertion Loss

The effect of insertion loss can also be seen at the far left side of Figure 5. At zero working distance, the irradiance measurement for the LED array without a lens system is higher than the irradiance with the parallel or overlapping lens systems. This is because of the insertion loss introduced by the lens system. These losses include aperture effects, absorption in the transmission mediums, scattering from discontinuities in the lenses and Fresnel loss. Aperture effects may arise from limited physical size of the lens or opaque components in the lens mounting structure. For a system with a single LED, a larger lens is better able to collect the light. However, the aggregate power and power density from an array will be increase as the number and density of LEDs increase. Therefore, the benefits of increased light collection efficiencies of larger lenses must be balanced against the advantage of more tightly packed LEDs.

Material Losses

The choice of materials used in the UV lens systems is very important. Lens arrays for visible light applications are often fabricated from molded transparent plastic materials. This process allows for simultaneous fabrication of the array support structure and lens medium in a simple, high volume process. However, many materials used for visible wavelength molded optics are absorptive at UV wavelengths. Even with low absorption rates, the high power levels in most industrial applications will result in long term accumulated damage and degradation. Quartz is commonly used in mercury based optics with high UV irradiance levels in order to withstand damage.

At this time most UV LEDs emit in the longer wavelength UVA region of the UV spectrum which is less damaging. Scattering losses come from defects on the surface or within the lens component. Fresnel losses occur at discontinuities in index of refraction, for instance at an air-lens interface. Fresnel losses for common UV transparent materials will be in the range of 3-5% per air-lens interfaces. They can be reduced though anti reflection coatings provided the coating materials are properly selected for good UV transparency and long term wear. Since LED light sources emit over a narrow wavelength band, the optical thickness of the anti reflection coating can be tightly tuned to be very effective.

Edge Effects

Good uniformity is often important for consistent materials processing. The perimeter of the processed area is influenced by edge effects of a finite LED array. Edge effects are due to the angular spread in the optical beam. The light from several LEDs may fall upon a target placed at the center of the array at a relatively long working distance. The irradiance will drop as the target is moved away from the center of the array even if the working distance is the same. The onset of edge effects depends on the ratio of the array width to the working distance and angular spread of the individual beams. This effects is illustrated in Figure 3. Each region at position B is illuminated by one LED, so the optical power is relatively uniform. Of course there will still be variations in the irradiance due to component variations such as LED to LED output or lens to lens throughputs. At position C a working distance of 2L, there will be an additional variation that can be attributed to the “edge” effects as the working distance to array width ratio increases. The central area will receive illumination from 2 LEDs while the outer regions will receive illumination from only one. Position D has a working distance of slightly more than 3L. Again, the outer region receives illumination from only 1 LED while the region at the very center receives light from all 4 LEDs. This systematic increase in the dynamic range of illumination is due to the increase in the ratio of the working distance to array width. Alternately, edge effects are minimized when illuminating objects at short working distances from large arrays. For a system with an infinitely wide LED array, there would be no edge effects and the irradiance would not change with working distance.

Alignment of Lenses

The alignment of a lens relative to its corresponding LED is very critical. An unintentional displacement in the direction perpendicular to the plane of an LED array will result in a change in the angular cone of the light beam and a change in the optical collection efficiency of the lens. Misalignment parallel to the plane of the LED array results in a pointing of the light beam in the direction of the lens offset. The amount of beam pointing can be estimated from the principle ray following a ray that originates from the center of the LED and passes through the center of the lens system. The lateral displacement in the plane of the lens will be multiplied in the plane of the illumination target. The multiplication factor is the ratio of the distance from the lens to the illumination target divided by the distance from the lens to the LED. Generally, this factor is very large, so both the lenses and LEDs must be very accurately positioned. The influence of misalignment of the lenses can be seen by carefully studying the irradiance pattern in Figure 4B produced by parallel beams.

Beam Pointing

The effect of a lens offset relative to its LED can be used constructively as beam pointing. By coordinating the beam pointing of multiple LEDs in an array, the light can be forced to overlap and combine onto a single region. This concentration of the light can increase the irradiance at a fixed location from the LED head as illustrated in Figure 4C. At 7.5 cm, the irradiance with the overlapping and combining lens array is 3 times greater than the irradiance with the partially collimated beams and 22 times greater than the irradiance from the system without a lens. In addition, the irradiance is 1.6 times higher than the irradiance at the emission window (z=0) point for the system without any lenses. The irradiance is increased while preserving energy conservation because the illuminated area is decreased. The process also preserves the etendue of the system since the angular diversity of the converging beams offsets the reduced illumination area. Based on the relative offsets of the lenses, the beams will converge at a fixed working distance from the LED array. Beyond the converging distance, the irradiance decreases as the optical beams cross and then begin to diverge. These trends can be seen in the curve with open circles in Figure 5.

Care should be taken in setting the working distance and the beam pointing for a particular application. As the angle of beam pointing is increased, the efficiency of light collection drops as beams on the far side of the lens are no longer captured and redirected. This places a constraint on the number of LEDs that can be made to place light on a particular point.

Scalability and Extremely Large Arrays

Due to their modular nature, arrays of LEDs and lens combinations can be readily scaled for large applications. By comparison, extremely large mercury discharges become difficult to operate because of high electrical breakdown starter voltages and bulb sag with long high temperature usage. Thermal contact with mechanical supports to the vessel may result in uneven temperatures and expansion strains leading to cracks. The demonstrated methods for using lenses to handle LED array discontinuities can be extended to extreme applications to produce UV light sources to span very large conveyors.

Summary

This paper has presented the fundamental physical characteristics of UV LEDs that form the optical requirements for high power LED arrays. Important topics such as lens characteristics and beam pointing have been developed. Data from practical implementations of UV LED arrays with gradually expanding beam or overlapping and combining lenses arrays to increase the irradiance by a factor of 7 or 22 over the same array performance without lenses.

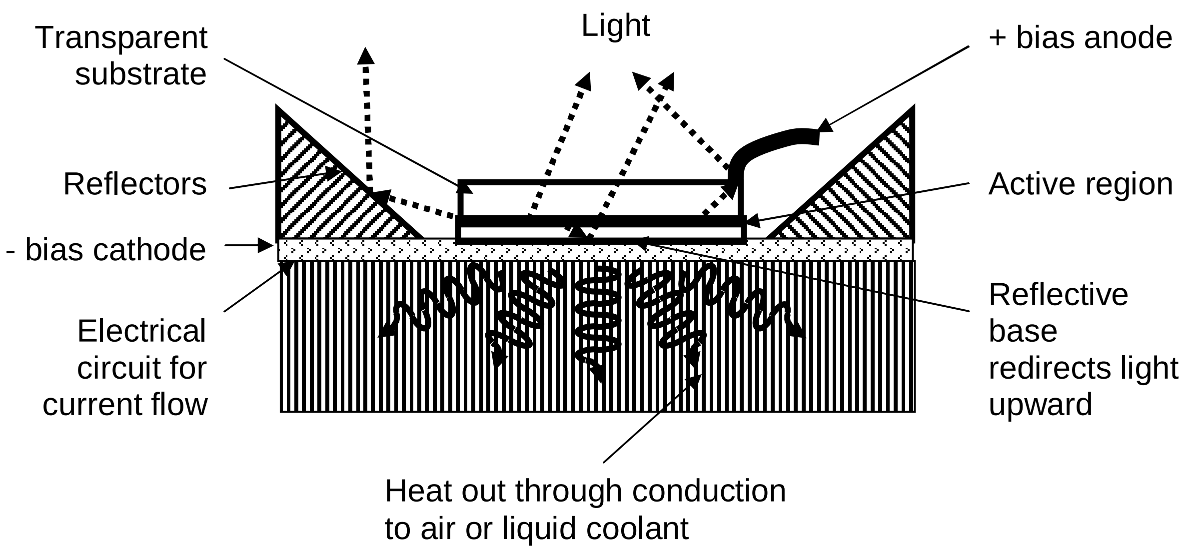

Figure 1 Cross section of typical UV LED

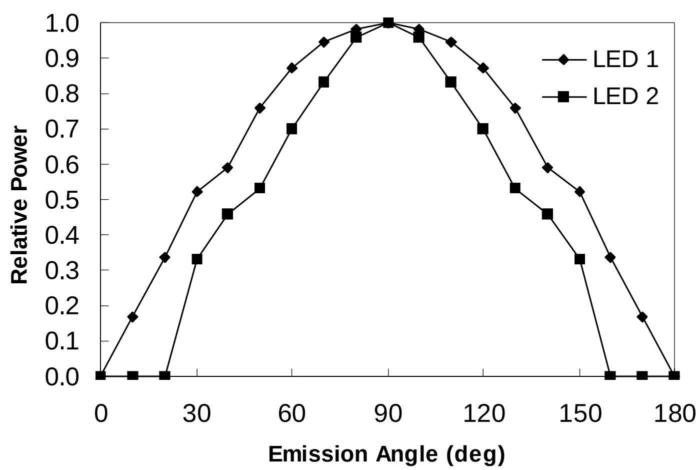

Figure 2 Far Field Pattern of UV LEDs

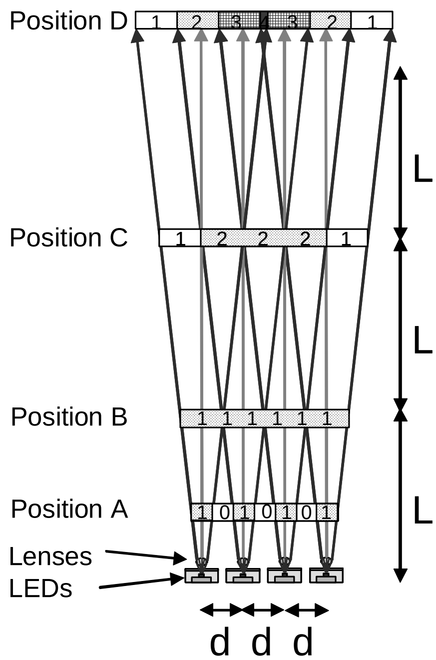

Figure 3 Schematic of Gradual Expanding Beams

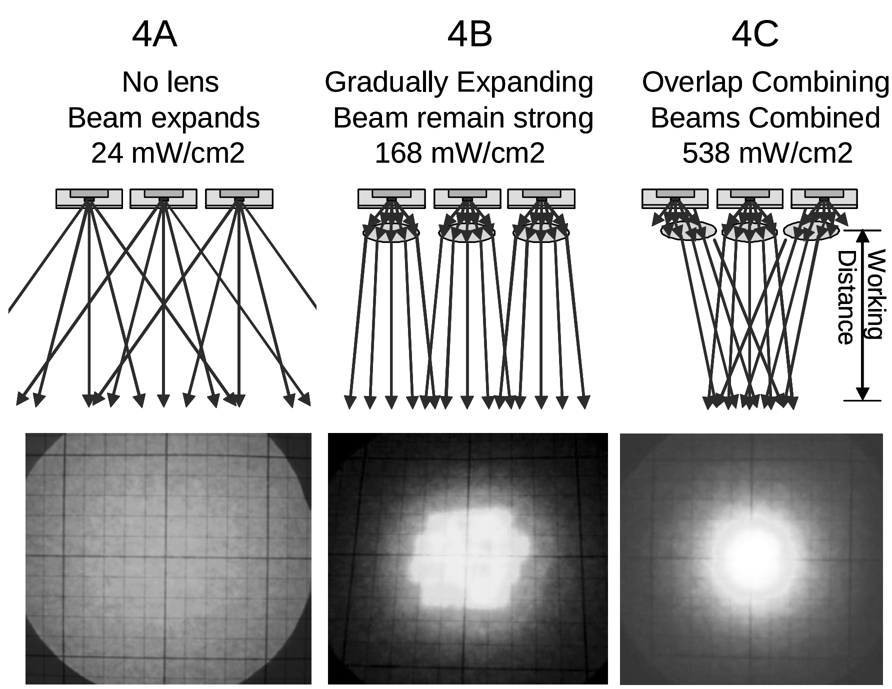

Figure 4 Comparison of LED Far Field Pattern

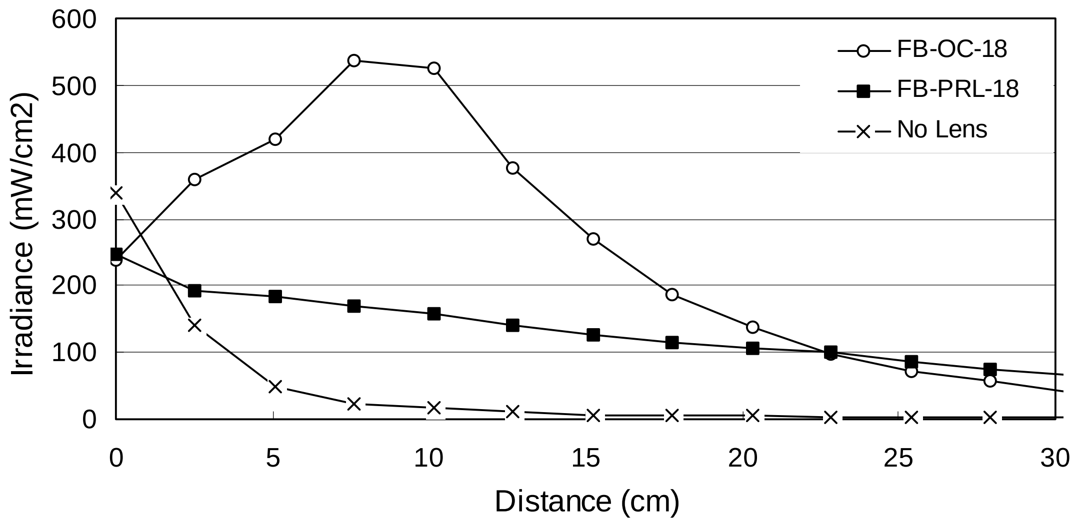

Figure 5 Graph of Irradiance vs. Working Distance