# UV-LED Overview Part II — Curing Systems

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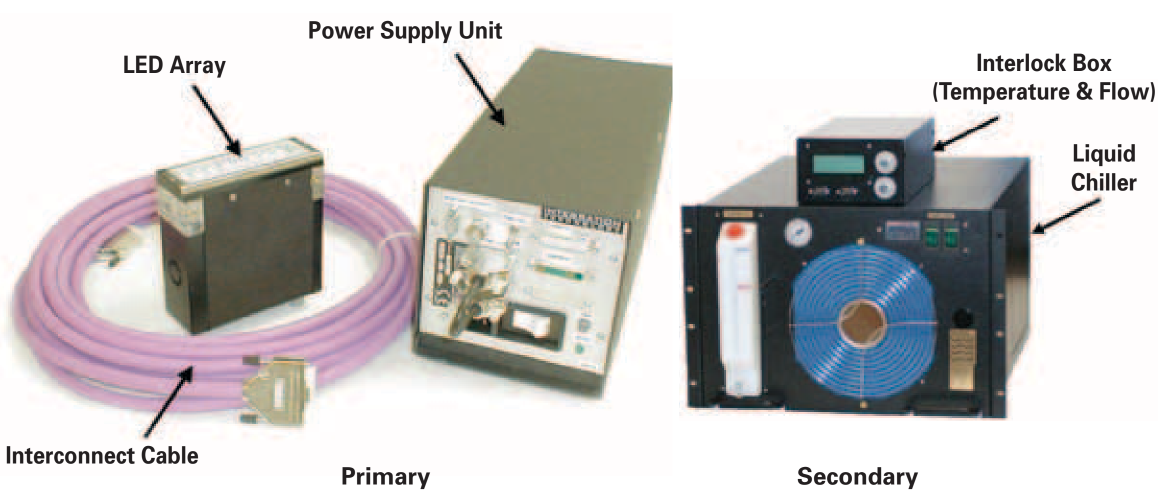
*This article is the second installment in a three-part series designed to consolidate key principles and technical information regarding the science and engineering behind ultraviolet light-emitting diodes (UV-LEDs). If you have not yet read "Part I—Operation and Measurement" in the July/August 2010 issue, you may want to do so before continuing with Part II.*

The best approach when tackling any new topic is to begin with a study of relevant terminology within the context of the defined subject matter. Without a firm grasp of the common language, key concepts often appear disconnected and it can be difficult to achieve full comprehension or communicate effectively within the marketplace. With emerging technologies such as UV-LEDs, an additional challenge in learning the jargon lies in the fact that the language has not yet been properly established or defined with respect to the UV curing industry, let alone consolidated for easy reference. This increases the chances that many of us are not using the same words or are using them incorrectly.

Furthermore, if the words have multiple meanings or if the definitions of the words are not apparent, their usage can lead to confusion or misunderstandings between suppliers and customers as well as within companies. How many conversations have each of us had regarding UV-LEDs in which we either assumed the other party understood what we were saying or we pretended to understand what

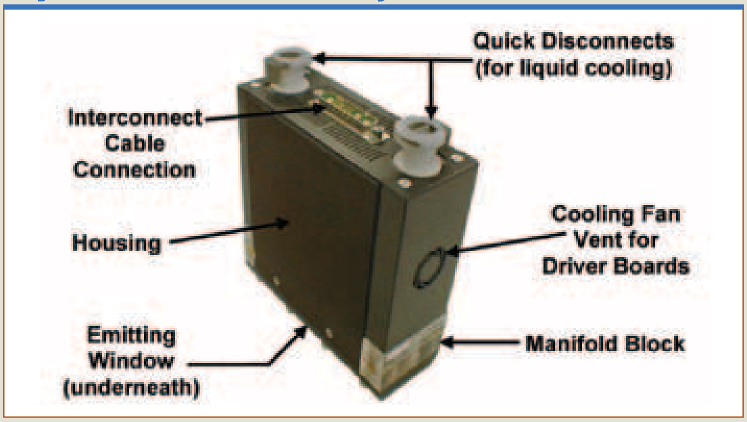
## Figure 1

UV-LED system components



## Figure 2

### Liquid-cooled, UV-LED array




they were communicating to us simply because of insufficient knowledge of the words being used in the conversation? In order to document the language of UV-LEDs, educate the UV-curing industry and separate the truth from current marketing claims, this article will outline key terminology within a larger discussion of the integration of LED chips into UV-curing systems.

### UV-LED System Components

All UV-LED systems designed for integration onto an OEM or host machine consist of three primary and two secondary components. While some companies within the industry may elect to use unique marketing names for these items, the primary components are generally known as the LED array, the power supply unit (PSU) and the interconnect cable. Two common secondary components generally necessary for LED arrays currently rated at or above 4 W/cm$^2$ are the liquid chiller and the flow and temperature interlock. Sample images of the primary and secondary components are provided in Figure 1. Ancillary items not shown would include material handling equipment, mounting brackets and light shielding.

The LED array of Figure 1 is a curing assembly that provides a function similar to that of a traditional UV lamp head or irradiator. Often the name “LED array” is shortened to array or generically referred to as the head. It is not uncommon to hear an array incorrectly called a lamp head as this has always been a frequently used term in the UV-curing industry. A standard UV-curing array houses the LED chips and, in many cases, includes a self-contained cooling fan when the maximum UV irradiance is less than 4 W/cm$^2$. In arrays designed for peak irradiances above 4 W/cm$^2$, liquid cooling is more commonly used. For these arrays, tube fittings or quick disconnect couplings are attached to the housing or manifold, and the LED-chip cooling fan is removed. The fittings or disconnects are the means by which the liquid circulation chiller is connected to the head and its internal cooling tubes. If a cooling fan is present in the array of a liquid-cooled system, it is specifically for cooling other electrical components such as the driver boards. A detailed photo of a liquid-cooled LED array is provided in Figure 2. It should be noted that LED arrays are supplied in a wide range of shapes, sizes and designs and while Figure 2 highlights common features of a standard array, it is just one example.

A fully assembled LED irradiator typically includes an emitting window that physically protects the LED chips within the assembly. The window is commonly made from a flat piece of quartz or borosilicate glass located on the head between the LED chips and the media or part being cured. Borosilicate—which is a colorless, silica glass with a minimum of five percent boric oxide—is less expensive than pure quartz and offers exceptional thermal-shock resistance and strength in comparison to both pure quartz and lower quality glass. The emitting window is sometimes chemically treated to further enhance its optical properties. This treatment can give the window a purplish or yellowish tint. The actual emitting window is hidden from view in Figure 2, but it can be seen on the exposed top surface of the LED array in Figure 1.

The power supply unit, often called a PSU, is an electrical enclosure that contains the parts necessary to power and control the array. It also serves as the communication link to a host machine. The driver board(s), which will be discussed in more detail in “Driving the LED Array,” directly power the LED chips and can either be mounted inside the array housing as in Figure 2 or in the PSU itself. The interconnect cable is the final piece of primary equipment. It provides the electrical connection between the LED array and the power supply.

The array, power supply and interconnect cable are required for a fully operating UV-LED system; however, not all three components necessarily need to be supplied by the UV equipment manufacturer. In some cases, integrators or end-users may elect to design their own power supply and/or interconnect cable. Though great care should be taken to assure that the proper specifications are met, they may even decide to buy smaller LED array packages (called modules) and build their own irradiator.

A liquid chiller is the cooling system most often required for LED arrays with UV outputs greater than 4 $W/cm^2$. The chiller is used to ensure the LED chips and wire bonds remain at the correct operating temperature. It does this by removing unwanted heat that is a by-product of the electroluminescence process discussed in Part I. While the UV supplier can furnish the chiller as part of the curing system, it is often more cost-effective for the integrator or end-user to purchase an off-the-shelf chiller locally or to design their own. The required cooling capacity will vary depending on the array configuration, so be sure to consult with the UV system's operating manual or with the supplier before making a decision. If the cooling system is not correctly designed or integrated into the system, the LED chips will fail prematurely.

The temperature sensor and flow meter monitor the coolant conditions at the inlet and outlet of the array. If the temperature of the circulating coolant at the array inlet and outlet exceeds a specified set point or if the outlet flow rate drops below its predetermined setting, the interlock circuit switches off the LED array. This is a safety feature designed to ensure that the correct operating temperature of the LED diode is maintained and that overheating and destroying the wire bonds is avoided. It should be noted that the interlocks can either be supplied by the LED system manufacturer or furnished by the integrator or end-user.

## Packaging UV-LEDs

LED, chip, die and diode all refer to discrete, individual semiconductors that emit light when current flows through them. These four terms are used interchangeably whether referring to single or multiple LEDs. (For additional information on diode operation, refer to Part I.)

In general, UV system designers source LED chips directly from semiconductor manufacturers who have binned or categorized them according to a desired wavelength tolerance and forward voltage. UV system designers engineer the chips into an irradiator assembly that is like electrically powered, cooled with air or liquid, and equipped with a controls interface and, sometimes, optics. This is similar to the way in which electrode and microwave bulbs are sourced and then integrated into a lamp head assembly or irradiator and connected to a power supply unit. A basic LED package can consist of one or several chips, while an LED array usually contains a large number of chips arranged in a matrix pattern. Both terms refer to an arrangement of LEDs that are physically and electrically assembled together and include a means for the entire assembly to be electrically connected to another device. When a heat sink and, occasionally, optics are added to the LED package, it is often referred to as an LED module. Several LED modules can be joined together to form an even larger LED array.

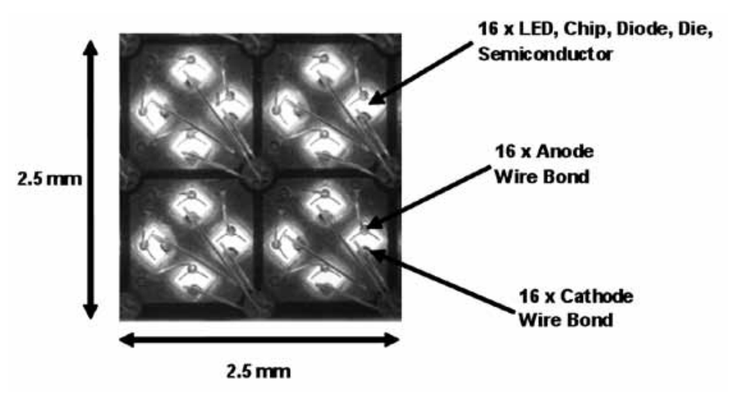
Some LED chip suppliers sell individual diodes that can be fully integrated by the UV system manufacturer into customized modules or LED arrays while others only provide their own engineered modules. Purchasing individual diodes enables the UV system manufacturer to better control and differentiate the final system design. Purchasing pre-packaged modules, on the other hand, eliminates some of the engineering but also forces UV system developers to work within the size and performance constraints of an existing assembly that may not have been designed with the necessary curing application in mind.

While there are many manufacturers of visible LEDs with production facilities located throughout the world, only about half a dozen are capable of developing and producing chips that emit wavelengths in the ultraviolet region. Some of these manufacturers include large, well-known, multinational brands such as Nichia, Fox, Nitride and Cree. As with any business, each manufacturer of UV-LED diodes has strengths and weaknesses, as well as established corporate strategies that determine which markets they pursue. Since the UV-LED market is extremely small in comparison to that of the visible and infrared LED markets targeted toward the commercial lighting, automotive, communications and securities industries, not all of the capable manufacturers are interested in producing chips for UV-curing applications. Furthermore, the flexibility of the UV-LED manufacturers with respect to the diode or module configurations they are willing to sell varies among an already small list of potential producers.

LED chips are made from very tiny slices of semiconductive material such as silicon or germanium that are doped or impregnated with additives to produce specific n-type and p-type conductivity (as discussed in Part I). This should not be confused with additive UV lamps in which the internal gas mixture is doped with iron, gallium and indium (among others) in order to shift the spectral output of a standard mercury lamp. Individual LED chips vary in size from a fraction of a millimeter to a few millimeters square and are typically less than a hundred microns thick. A wire bonding process that employs ultrasonic

## FIGURE 3

### 16 LEDs with a wire bond at each anode and cathode




welding or thermal compression is used to electrically connect LED chips to a printed circuit board (PCB). One wire bond is made at the chip's positive terminal or anode while the other is made at the negative connection or cathode.

One of the many advantages characterized by LED sources is the inherent "scalability" of the technology. An LED package can consist of just a single LED chip or thousands of interconnected dies. As a result, an LED source could, in principle, be fabricated to any size and shape; whereas, conventional microwave and electrode UV sources are restricted to a much narrower envelope based on bulb technology and microwave cavity sizes.

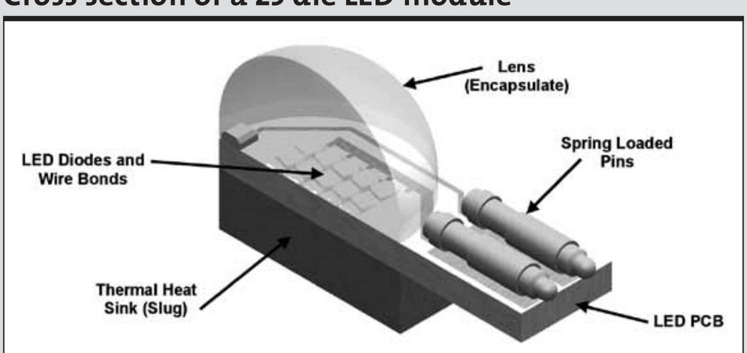
In practice, most UV-LED arrays are likely to contain hundreds or even thousands of LED chips in a given assembly. The more chips, the more involved the manufacturing process and the more expensive the final assembly. For example, if there are 400 LED chips in an array, then 800 wire bonds are required. It should be noted that the wire bond is thermally sensitive and can be destroyed if the heat, an unwanted by-product of the electroluminescence process, is not sufficiently removed. Figure 3 shows a magnified image of 16 separate LED diodes taken from a larger assembly consisting of 100 chips. Two wire bonds are visible for each diode with all 16 mounted in a matrix to form a larger square pattern.

The wire-bonded diodes and PCB are secured to a metallic heat sink or slug. The heat sink is used to draw heat away from the diode and wire bonds. A flat encapsulate that is transparent and made of silicone, borosilicate glass or quartz is placed over an individual LED chip or over several LED chips for added protection. Alternatively, a dome-shaped lens made of silicone is sometimes used to control the UV rays so that they are uniformly directed at the media or part being cured. A cross sectional illustration of one type of LED package with a lens is shown in Figure 4. In this assembly, there are a total of 25 LED chips. There are 10 diodes shown in full while the cross section of the drawing splits one row of five in half.

As previously mentioned, several LED modules can be arranged together to create a physically larger LED matrix or head. The use of multiple plug-in modules, each containing a diode matrix, provides the benefit of being able to make "plug-and-play" repairs in the field. This reduces downtime or the need for a backup array as only faulty or spent modules need to be replaced. Alternatively, LED arrays are sometimes designed so that the UV-LED chips, PCB and metallic heat sink form one large, uniform assembly that spans the desired curing width. Arrays of this nature are non-serviceable and cannot be taken apart in the field as all chips in the assembly are wire bonded directly to a single PCB and heat sink. As a result, the entire array must be returned to the manufacturer for any necessary die repairs. Figure 5 provides examples of plug-in modules,

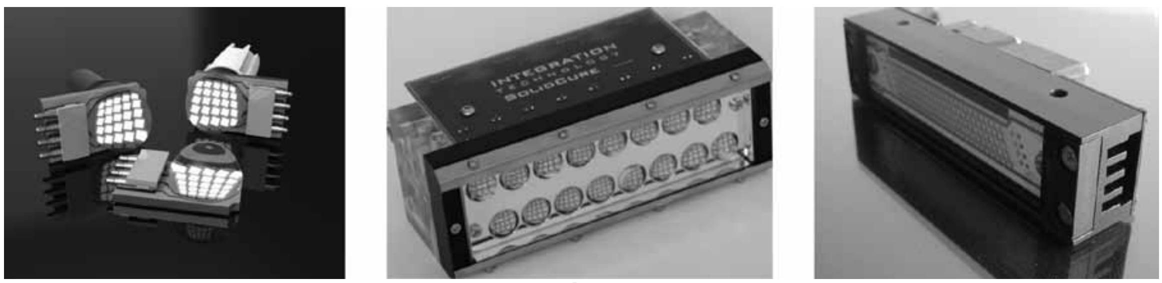
## FIGURE 4

### Cross section of a 25 die LED module



## Figure 5

**UV-LED arrays (a) three plug-in modules, (b) 1 LED array encompassing 16 plug-in modules, and (c) 1 LED array with 100 diodes all mounted to a single PCB and heat sink**




a b c

a serviceable LED array and a non-serviceable LED array.

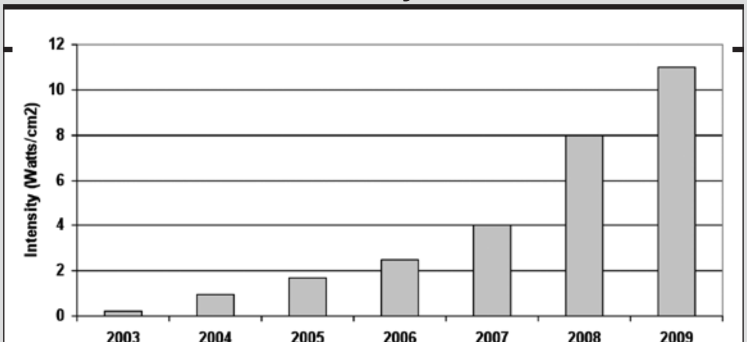
Part I discussed the nearly monochromatic nature of UV-LEDs and how LEDs rated at 395 nm and greater emit more than five times the UVA intensity at these wavelengths than conventional electrode and microwave UV-curing lamps do at their respective peaks. Even greater irradiance levels can be achieved through the use of optics and driving techniques. Figure 6 illustrates the rapid growth in UV output for a 395 nm chip over the past seven years. The increase can be attributed to gains in understanding the science behind LEDs, improvements in the manufacturing and quality processes, and new combinations of semiconductor materials.

As with traditional microwave and electrode UV-curing applications, sufficient levels of both irradiance and energy density over a specific range of ultraviolet wavelengths are required for complete cure. When UV irradiance is taken over a period of time, it is known as the energy density or dose. For example, an intensity of 1 W/cm$^2$ exposed for 1 second is equal to 1 J/cm$^2$ of energy density. The design and manufacture of the LED chip, the current flow through the die and the distance of the array from the substrate all contribute significantly to the array's UV irradiance or intensity at the substrate surface. Alternatively, the total dose delivered to the substrate is a factor of the output of the individual dies, the total number of chips used and the end-use process speed. Both irradiance and energy density measurements should be referenced with the wavelengths generated by the array. Today, only longer UV and shorter visible wavelengths in the range of 350 nm to 430 nm are generated by LEDs for use in UV-curing applications. Commercially, these dies have peak irradiances at 365, 375, 385, 395 and 405 nm with tolerances of up to ±15 nm.

For certain types of inks and coatings, a fourth variable (heat) is sometimes necessary to achieve a successful cure. In most cases, heat transferred to the cure surface by the LED array is negligible as there is no infrared component in the spectral output of an LED array. For slower process speeds, however, some of the radiated UV energy that is not absorbed by the chemistry is converted to heat at the substrate. This heat, however, is less than what is generated by electrode and microwave UV systems. The advantage of using UV-LEDs is that if heat is required for the application, it can be controlled

## Figure 6

**Advancement of UV intensity for 395 nm LEDs**



independently of the UV device and, if it is not required, it is essentially eliminated.

It is critical that the correct combination of irradiance, energy density, wavelength and heat be used in order to cure a given ink or coating at the desired application process speed. For a properly selected wavelength source, irradiance and energy density work together like time and temperature in a thermal process. Fortunately, there are various combinations of irradiance and energy density that may result in an optimally cured product. Most UV-curing processes, therefore, occur not at a single irradiance or energy density level, but within a "process window" that should be established during the process specification trials.

Confusion in selecting the optimal UV-LED product originates in the fact that most UV-LED suppliers simply quote the peak wavelength and maximum irradiance at the emitting window as well as the physical dimensions of the LED matrix. Not all arrays that seem to be identical in these specifications, however, will provide similar irradiance, energy density and heat at the substrate over an identical range of wavelengths. This can be a bit misleading and is the single biggest difficulty in comparing UV-LED systems or in selecting the best system for a given application.

## Cooling the LED Array

The overall efficiency of an LED semiconductor chip refers to how much of the electrical energy supplied to the system is directly converted into useable light energy. Technical limitations presently render UV-LEDs around 10 to 20% efficient for longer wavelengths (395 and 405 nm) and less than 10% for shorter wavelengths (365 nm). Visible and infrared LEDs, on the other hand, are in the range of 40 to 50% efficient while electrode UV systems are around 25% efficient.

Inefficiencies with UV-LEDs result in the production of large quantities of heat. In general, diodes with greater irradiance ratings generate more heat than diodes with lower irradiance ratings. Since LEDs with longer wavelengths such as 395 and 405 nm currently emit the most irradiance, they generate more heat than shorter wavelengths and must be liquid-cooled for maximum output. The heat is not radiated in the form of infrared energy but is instead a by-product of the electroluminescence process. If the heat is not removed, the wire bonds and LED chips, which cannot exceed a sustained temperature of around 125°C, will suffer catastrophic failure. In addition, the surrounding frame, manifold or housing of the array assembly will absorb the heat and radiate it out toward the substrate or part being cured.

In the near future, UV-LED efficiencies will improve and the cooling requirements will gradually decrease. While there are always exceptions, the general rule of thumb today is that arrays with outputs of less than 4 W/cm$^2$ can be sufficiently cooled with air; anything greater is typically cooled with a liquid-circulation chiller. An advantage of liquid-cooled systems is that there is minimal air movement around the UV-light source. This makes for a cleaner process since cooling air frequently stirs up airborne contaminants and allows arrays to be mounted close to thin or fragile substrates without disturbing them. In addition, liquid-cooled systems are typically more compact and can be more easily located in tight spaces. It is always important to note that exact cooling requirements vary depending on the array design and size so be sure to consult with the supplier or respective operating manual. In the case of air-cooled systems, the fan will likely be provided as part of the array assembly. Liquid chillers, on the other hand, can be provided by either the UV system manufacturer or sourced independently by the integrator or end-user.

Most industrial chiller companies recommend using a mixture of industrial inhibited glycol and water as the circulation coolant. An inhibited coolant prevents the formation of scale and corrosion while simultaneously protecting the metals. In addition, it also offers protection against algae and bacteria, provided a minimum concentration level is used. Ethylene glycol has better thermal transfer properties; however, propylene glycol is more environmentally friendly. Both are marketed in North America under the brands DOWTHERM™ and DOWFROST™, respectively, and can typically be purchased in either concentrated or diluted form in small volumes through chiller suppliers. It is good practice not to mix different types or brands of glycol as this can precipitate some inhibitors out of solution. The net effect is a reduction in the effectiveness of the coolant and possible particulate buildup at various locations within the closed-loop system.

The DOW Chemical Company recommends that concentrations of its products be maintained between 25% and 60% glycol. Concentrations in the lower range result in better heat transfer; however, using less than 25% glycol can lead to corrosion and less than 20% glycol will result in bacterial contamination. Commonly used proportions are 25%-30% glycol to water. Distilled or reverse-osmosis water can be used to dilute the glycol. De-ionized water can sometimes be used for dilution as long as the de-ionized state of the liquid is not maintained. Maintaining a de-ionized state can result in the breakdown of certain metals in the system. Most chiller suppliers strongly discourage against the use of regular tap water. Similar inhibited coolants are available from other manufacturers and may be more accessible given your location. Before selecting a chiller or before filling the reservoir, make sure you consult with the UV-LED system and chiller suppliers, their respective manuals, state and local codes, and the corresponding Material Safety Data Sheet.

Today, the decision of whether to cool an LED array with air or liquid is primarily based on the maximum irradiance level. Higher irradiance LED systems tend to incorporate liquid chillers because they are the most effective way to remove unwanted heat and result in a more compact array. Lower irradiance LED systems that incorporate air-cooled arrays emit less UV, making it more difficult to cure some materials at faster speeds. This is the trade-off when air cooling is used. Failure to provide sufficient cooling with either air or liquid will result in catastrophic and premature failure of the wire bonds and LED chips. A temperature sensor and flow meter interlock is a great safety feature that can and should be built into systems using liquid chillers. If the temperature of the circulating coolant at the array inlet and outlet exceeds a specified set point or if the outlet flow rate drops below its predetermined setting, the interlock circuit switches off the LED array. Do not assume, however, that your system is equipped with an interlock. You should always consult with the operations manual or your supplier to be sure.

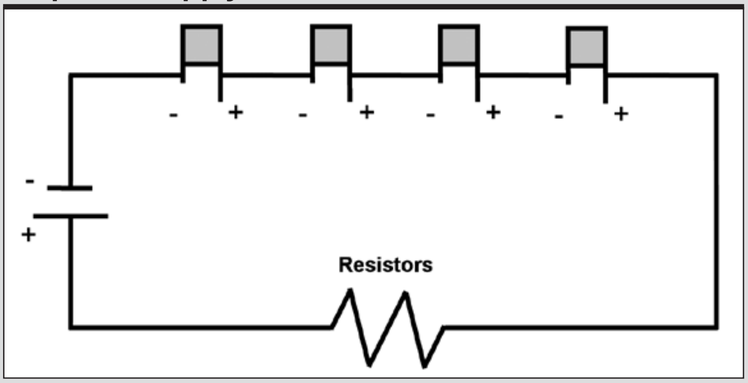
## Driving the LED Array

Traditional electrode UV-curing systems utilize an ignitor to strike a 2 to 4 kilovolt arc across the bulb in order to vaporize the mercury and emit UV. Ballast, choke or transformer combinations are wired into the circuit to stabilize the amount of current flowing through a struck bulb and provide for various UV power output levels. LEDs, on the other hand, are entirely solid-state devices that emit ultraviolet light immediately when connected to a low-voltage, DC power source and do not require a high-voltage ignitor. Each LED chip is designed to operate between 20 and 500 mA and between 2 and 4 volts DC. The amount of UV irradiance emitted from an LED is directly proportional to the amount of current passing through the device; however, if the design voltage or current rating of any individual LED chip is exceeded for an extended period of time during operation, the chip will fail.

LEDs can be connected in series or parallel circuits as illustrated in Figures 7, 8 and 9. While all three simple circuits demonstrate the connection of four diodes, UV-curing arrays will typically have hundreds or even thousands of individual LEDs wired into a single chain. In a series installation, if one LED fails, current flow through the circuit is interrupted downstream from the faulty LED. Parallel circuits have the

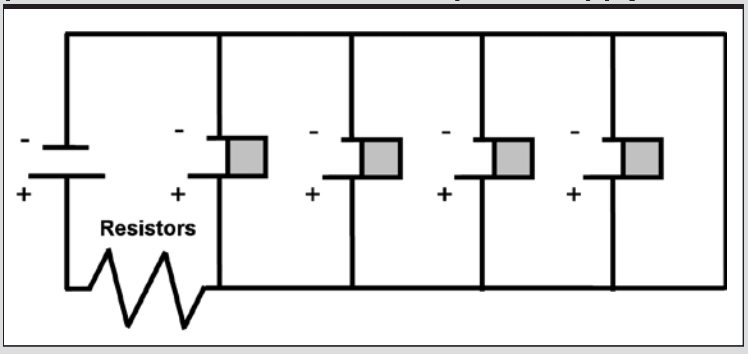
## Figure 7

**Four LEDs wired in series with resistors and a DC power supply**



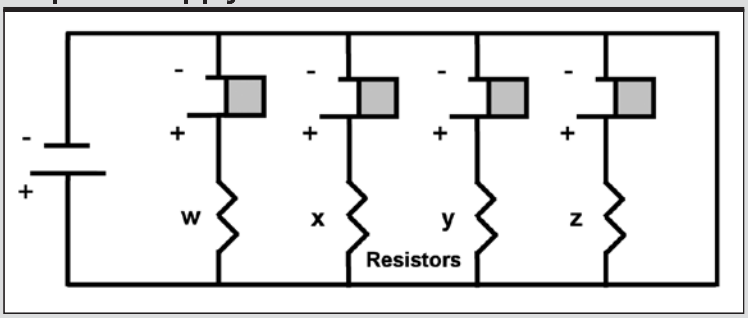

## Figure 8

**Four LEDs with identical voltage ratings wired in parallel with resistors and a DC power supply**



## FIGURE 9

**Four LEDs with different voltage ratings wired in parallel with four different resistors and a DC power supply**




advantage of continued operation of all functioning LEDs even if one or more LEDs fail. In either type of circuit, it is important that the anode and cathode connections be alternated. This is because LEDs have polarity and current will only flow in one direction. Placing two anodes or two cathodes in sequence will disable the circuit.

In all three simple circuits, resistors are precisely sized to ensure the correct voltage drop and current flow across each LED. Insufficient voltage and current will yield less than optimal UV output, while too much can lead to premature failure of the dies. When LEDs are wired in parallel, as illustrated in Figure 8, they must all have the same voltage rating. Otherwise, current flowing through each leg of the circuit will vary and result in some LEDs not lighting or not all LEDs emitting the same light output. If LEDs have different voltage ratings, then appropriately sized resistors must be placed in each leg of the circuit to balance the current flow. This is illustrated in Figure 9 with resistors w, x, y and z rated at different values.

In practice, the use of resistors to regulate voltage and current within an LED circuit is actually quite inefficient as resistors generate heat and cannot easily accommodate fluctuations in die tolerances and operating temperatures. Even the slightest variation in running conditions can produce wide swings in UV output and chip lifetime hours. Producing systems with multiple power levels is also challenging since it requires the use of many different resistance levels in order to vary the current through the circuit as a means of changing the amount of UV emitted from each diode. As a result, UV equipment manufacturers generally power LEDs with regulated, constant-current drivers and employ an optional technique known as Pulse Width Modulation (PWM) when it is necessary to vary the UV output.

The use of constant-current drivers enables each and every LED chip to always experience a non-fluctuating and continuous current when powered. The LEDs are either ON or OFF with no variability in irradiance. For applications that require multiple power levels, PWM is used to generate an almost infinite number of outputs. PWM takes advantage of the nearly instantaneous response time of LEDs and works by quickly and efficiently switching current to the diodes between ON and OFF. The length of the pulsed current varies the proportion of ON and OFF time per cycle.

Figure 10 illustrates PWM output levels of 25, 50, 75 and 100% power. Duty cycle is defined as the proportion of ON time to the total cycle time (ON + OFF) and is expressed as a percentage. A low duty cycle corresponds to low power because the power is OFF most of the time, whereas 100% is fully ON, 0% is fully OFF and 50% means that the power is ON half the time and OFF half the time. It should be noted that the total cycle time or period, indicated by “P” in Figure 10, is constant across all four duty cycles.

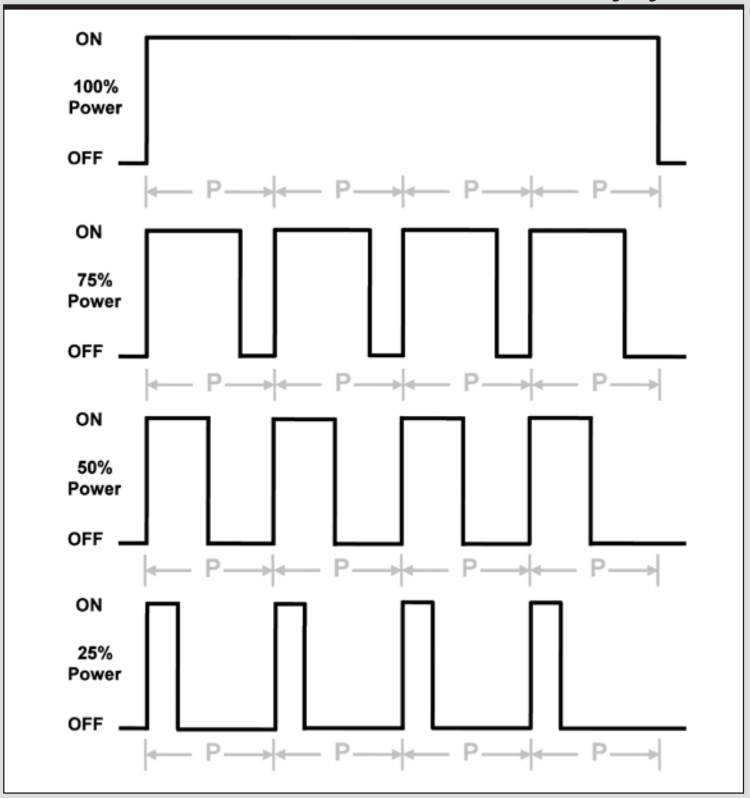
With PWM, the peak irradiance ($W/cm^2$) is the same for all power levels, but the duration of the pulsed current and, therefore, the duration of the pulsed irradiance, is varied so as to increase or decrease the total exposure time or energy density ($J/cm^2$). The two main reasons for using PWM to drive the UV-LED power levels, as opposed to varying the actual drive current through the LED circuit with resistors, are that PWM (1) provides truly instantaneous and infinitely variable control of the UV output and (2) prolongs the life of the chips. In addition, PWM provides for easy addressability of individual banks of LEDs or modules within an array.

The fast cycling or strobing of LEDs using PWM occurs at frequencies of 2 KHz or greater. A 2 KHz frequency means that there are 2,000 cycles (or current pulses) every second. While this high of a frequency cannot be detected by the human eye, an observer will notice that the LEDs become increasingly dimmer in appearance as the relative output decreases. With respect to an application using a PWM frequency of 2 KHz in which the media is traveling beneath the array at 0.5 meters per second, the UV source illuminates once every 0.25 millimeters of media travel.

The array driver boards are essentially printed circuit boards, (PCBs), although they are entirely different PCBs than the ones to which the individual diodes are wire bonded. The purpose of the driver boards is to distribute the DC voltage to the LED chips or modules in an array; deliver the necessary constant current; and provide the PWM capability of the system. The driver boards can either be mounted on the array or located remotely in the power supply unit. The advantage of mounting the boards on the array is that electrical noise can be minimized and the diameter of the interconnect cable can be reduced. There are many different types of drivers used to perform a wide variety of functions. As a result, the style of driver board used in LED systems will vary significantly between manufacturers.

## Figure 10

**PWM illustration of 25, 50, 75 and 100% duty cycles**




### Installing UV-LED Systems

The task of installing a UV-LED system is similar to that of installing a conventional UV system, but in some ways it is actually a bit simpler. Unlike conventional UV systems, LEDs generate no ozone; do not emit short wavelength UV which can attack many materials; do not require special filters for observation windows; often draw far less electrical power; create less airborne contamination near the media when liquid chillers are used; and possess none of the handling and disposal issues associated with conventional medium-pressure mercury vapor lamps. Installations on a host machine typically require mounting the array(s); frequently purchasing or designing and then connecting the chiller system; electrically powering the PSU; connecting the interconnect cable between the power supply and the array; providing a means for the I/O interface; and ensuring safe operation for the operator and the UV-LED system, as well as the host and ancillary equipment.

All UV output attenuates or decreases in magnitude as the distance between the emitting window and the substrate increases. As a result, most LED arrays currently on the market are typically mounted as close as possible to the substrate or object being cured. This distance is usually between 5 and 15 mm; although, it does vary by supplier and application. Most arrays are equipped with mounting holes or threaded inserts that allow the device to be secured to a host machine with a simple bracket designed by the integrator or the end-user. The array should be mounted so that it either spans the curing width of a static installation or can be physically moved by the host machine to cover a greater curing area. The duty cycle of an array equipped with PWM and the speed of the line can both be adjusted to achieve a range of energy density while maintaining a constant irradiance. In some cases, multiple arrays will need to be used to achieve the required energy density. Keep in mind that the focal point commonly referenced with conventional UV systems employing elliptical reflectors is not typically applicable for LED systems. While LED chips can be packaged in an arrangement so that all the UV rays are directed to a common location or manipulated with optics, this is not standard practice. Current UV-LED systems more closely resemble the flood profile of traditional arc or microwave systems.

The wavelengths emitted from diodes used in curing systems are

# UV-LED TERMINOLOGY

**Anode**—positive terminal of an LED.

**Binning**—process of sorting LED chips into groups according to peak irradiance, wavelength tolerance and forward voltage.

**Borosilicate**—strong, heat-resistant, colorless, silica glass that contains a minimum of five percent boric oxide, exhibits exceptional thermal shock resistance, and transmits a greater percentage of ultraviolet energy than glass. Common material used for the emitting window on a UV-LED head.

**Cathode**—negative terminal of an LED.

**Chip**—a fully functioning, minute slice of a semiconducting material (such as silicon, germanium and gallium arsenide) doped and processed to have p-n junction characteristics. Specifically, gallium nitride (GaN) is used to generate longer ultraviolet and blue-visible wavelengths. In referring to LEDs, chip is often used interchangeably with diode, die and semiconductor.

**Coolant**—liquid circulation material that flows over the heat sink in the LED array or module in order to (1) remove wasted heat energy produced by the electroluminescence process and (2) maintain the correct operating temperature of the LED chips and wire bonds.

**Depletion Zone**—the non-conductive boundary where the positive and negative sides of a p-n junction meet.

**Die**—a fully functioning, minute slice of a semiconducting material (such as silicon, germanium and gallium arsenide) doped and processed to have p-n junction characteristics. Specifically, gallium nitride (GaN) is used to generate longer ultraviolet and blue visible wavelengths. In referring to LEDs, chip is often used interchangeably with diode, chip and semiconductor.

**Diode**—common semiconductor device which is added to a circuit as a means of restricting the flow of electricity. It can generically be thought of as a switch or a valve. A key property of a diode is that it only conducts electricity in one direction. In referring to LEDs, diode is often used interchangeably with chip, die and semiconductor.

**Doped**—refers to an LED semiconductor material that has been impregnated with impurities to produce a specific n-type or p-type conductivity.

**Driver Board**—a printed circuit board (PCB) that distributes the DC voltage to the LED chips or modules in an array and provides the pulse width modulation (PWM) capability of the system.

**Duty Cycle**—the proportion of ON time in a pulse width modulation cycle to the total cycle time (ON + OFF) expressed as a percentage. A low duty cycle corresponds to low power because the power is off most of the time, whereas 100% is fully ON, 0% is fully OFF and 50% means that the power is ON half the time and OFF half the time.

**Electroluminescence**—an optical and electrical phenomenon inherent to LEDs in which a material emits light energy when an electric current is passed through it.

**Emitting Window**—flat, rectangular piece of quartz or borosilicate typically secured at the base of an LED head to protect the dies while simultaneously transmitting ultraviolet wavelengths.

**Encapsulate**—a transparent material used to physically protect dies and block moisture. It can either be flat or shaped into a convex lens. Modern LEDs use encapsulates made of silicone, while older LEDs were made of epoxy resins. Both silicone and epoxy resins fully surround the LED chip(s). Encapsulates made of quartz or glass generally do not surround the LED chip(s), but are used as a hard protective outer cover.

**Forward Bias**—occurs when the anode of an LED is connected to the positive terminal of a voltage supply and the cathode of the LED is connected to the negative terminal. The effect of a forward bias is that the positive holes in the p region and the negative electrons in the n region of a p-n junction are pushed from opposite directions toward the depletion zone. This significantly reduces the width of the depletion zone causing the electrons on the n-side to respond to the attractive forces of the holes on the p-side. The end result is the flow of electricity and the emission of photons.

**Forward Voltage**—the actual voltage across a semiconductor diode carrying a forward current.

**Interconnect Cable**—electrically connects the LED irradiator and the power supply unit.

**Interlock**—a temperature sensor and/or flow meter designed into the LED-cooling system to monitor conditions at the inlet and outlet of the array. If the coolant temperature exceeds a specified set point or the flow rate drops below a specified set point, the interlock circuit switches off the LED array in order to avoid overheating and destroying the individual diodes and wire bonds.

**LED (light emitting diode)**—semiconductive device containing a p-n junction designed to emit specific narrow band wavelengths within the electromagnetic spectrum via a process known as electroluminescence. When a forward bias voltage is applied to the LED, current flows from the p-side to the n-side (anode to cathode). As the electrons cross the depletion zone and fill a hole, they drop into a state of lower energy. The excess energy is released in the form of a photon. The energy of the photon is directly related to the amount of excess energy, while the wavelength of the photon is inversely related to the excess energy. In other words, the higher the excess energy, the shorter the wavelength.

**LED Array**—(1) packaged sub-assembly or module typically consisting of multiple LED diodes or chips that are individually wire bonded to a printed circuit board and then secured to a heat sink; (2) also refers to a full curing assembly which includes numerous modules or LED chips, as well as a cooling fan or tube fittings, a manifold block, an emitting window and a sheet metal or plastic outer housing. In some cases, a complete array assembly will also contain the driver boards. The array is similar in concept to a lamp head or irradiator in traditional UV-curing systems.

**LED Irradiator, LED Head or LED Light Engine**—a UV-curing assembly which includes multiple LED chips or modules, a thermal heat sink, a cooling fan or tube fittings, a manifold block, an emitting window, a sheet metal or plastic outer housing and, sometimes, the driver boards.

**LED Package**—an assembly containing one or several chips physically and electrically assembled together with a means of electrically connecting the entire assembly to another device.

**Lens**—transparent device used to physically protect LED chips, block moisture and evenly manipulate or spread the emitted UV radiation. Often made of silicone, borosilicate or quartz. See *encapsulate*.

**Liquid Chiller**—cooling system used to (1) ensure the LED chips and wire bonds remain at the correct operating temperature and (2) to remove wasted heat energy from the electroluminescence process.

**Module**—packaged assembly consisting of one or multiple LED diodes that are individually wire bonded to a printed circuit board which is then secured to a heat sink. A module often includes a silicone encapsulate or lens over the chips for protection and to block moisture. A module is an array, but several modules can also be assembled together to form a larger array known as a head or irradiator.

**Optical Device**—used to evenly spread or sometimes focus the emitted UV radiation from an LED module or array.

**Printed Circuit Board (PCB)**—part of the LED module or array to which the individual LED chips or diodes are wire bonded. The PCB provides the electrical interface between the LED chip(s) and the driver board(s).

**Plug-in-module**—packaged assembly consisting of one or multiple LED diodes that are individually wire bonded to a PCB which is then secured to a heat sink. A module often includes a silicone encapsulate or lens over the chips for protection and to block moisture. A module is an array, but several modules can also be assembled together to form a larger array known as a head or irradiator.

**Positive-Negative Junction (p-n junction)**—a specially engineered diode made by forming layers of semiconductive materials. Impurities or dopants are impregnated or doped into the semiconductor layers to create p- and n-type regions. These regions can be made from the same or different semiconductor materials. The two sides of the diode are referred to as the anode (+) and the cathode (-), respectively. Current is able to flow from the p-side of the diode to the n-side, but it cannot flow in the reverse direction.

**Power Supply Unit (PSU)**—a generic term often used to describe an electrical cabinet containing the DC voltage supply, I/O interface and AC power connection for an LED array. The power supply unit may also contain the driver boards. Alternatively, the driver boards can be mounted on the array.

**Pulse Width Modulation (PWM)**—efficient way of providing intermediate amounts of electrical power by varying the proportion of ON and OFF time per cycle. The peak irradiance ($W/cm^2$) is the same for all power levels, but the duration of the pulsed irradiance is varied so as to increase or decrease the exposure time or energy density ($Joules/cm^2$).

**Semiconductor**—a substance that can be made to conduct electricity or be an electrical insulator depending on its chemical composition. The conductivity of the semiconductor varies depending on the impurity (or dopant) concentration created during the manufacturing processes. Common semiconductor base materials include silicon, gallium nitride, gallium arsenide and gallium phosphide.

**Wire Bond**—refers to the electrical connection between the LED chip and the PCB. There are two wire bonds between each LED chip and the PCB. These wire bonds are made at the anode and the cathode of the chip.

**Wire Bonding**—the method of making an electrical connection between the LED chip and the PCB using ultrasonic welding or thermal compression.

currently between 350 nm and 430 nm. This renders all of it in the UVA and visible bandwidth range and none of it in the UVB and harmful UVC range. As a result, shielding is only necessary to reduce visual discomfort due to brightness and can be addressed using sheet metal, tinted polycarbonate and various other low-cost plastics. Potential eye and skin issues due to UVC are not typically a safety concern with the UV-LEDs presently on the market; however, it is always best to review this with the supplier and err on the side of caution.

Longer wavelengths also mean no ozone is produced since ozone is only generated when wavelengths shorter than 250 nm interact with oxygen. As a result, it is not necessary to ventilate or exhaust the system unless you are working with extremely heat-sensitive substrates when it is desirable to remove additional heat from the electroluminescence process. With UV-LEDs, there can be a buildup of heat around the exterior of the array depending on the design. While this is typically fine for the operation of the UV-LED equipment, it can create a situation in which the array may be hot to the touch. As a result, it is recommended that protection be provided to ensure that the operator or maintenance staff does not unwillingly come in contact with the surface of a powered array.

Power supply units for UV-LED systems are more commonly solid-state devices where the main electrical supply power can typically be anywhere between 100 and 240 Volts AC at either 50 or 60 Hz. Solid-state power supplies automatically accommodate for the given voltage, frequency connection and minor variations on the line; however, you should always consult with the UV-LED system's operating manual or with the supplier to be sure. A DC-voltage power supply is installed in the

UV system's PSU to power the driver boards and LEDs. Current draw on the main AC line for products presently on the market vary from a few amps to more than 20 amps for larger arrays. For some applications that require thousands of LEDs, current draw will be higher.

The interconnect cable connections, I/O interface and liquid cooling capacity, while straight forward, will vary with each UV-LED system. As a result, these specifications are not covered by this article and should instead be discussed directly with the supplier.

## Comparing LED Technologies

The following questions can be used as means of comparing UV-LED products on the market or can serve as a guide through the integration process.

- What terminology is being used that you do not understand? Always ask the supplier to clarify anything that is confusing.
- What components are supplied by the UV system manufacturer (module, array, interconnect cable, power supply unit, cooling fan, chiller, interlock, mounting bracket)?
- What components do you want to source locally or design yourself (power supply unit, chiller, interlock, mounting bracket)?
- If supplying the chiller yourself, what size tube fittings or disconnects are supplied with the array?
- What is the necessary cooling capacity for the chiller in terms of wattage, flow rate, temperature and pressure?
- What type of coolant mixtures are required or restricted by the chiller and UV-LED system suppliers?
- Are there any health or safety concerns regarding the coolant?
- What are the local and state codes for use and disposal of the coolant?
- Can the array be repaired in the field or must it be returned to the manufacturer?
- Is the UV array powered with PWM or a constant current? Which is better for your application?
- What length interconnect cable does the application require?
- If the UV-LED array must move to provide full UV coverage, is the interconnect cable high-flex and what is the minimum bend radius?
- At what distance should the UV-LED array be mounted from the substrate or part being cured?
- What is the I/O interface?
- Does the UV system need to be controlled by a host system or is it equipped with a local operator interface?
- Do you want a "plug-and-play" solution or a partial solution that requires additional engineering?
- What is the supply voltage and main AC current draw for the entire system?

As you move forward with your investigative study of UV-LEDs, make sure you are comfortable with the terminology. For convenience, a glossary of commonly used UV-LED terms has been provided as an appendix to this article. The importance of word usage cannot be emphasized enough. Without a firm grasp of the common language, the progress of your project will likely be delayed. Worse yet, you could proceed down a development path that is not best for your particular application or you could completely miss an opportunity that may propel you ahead of your competition. If you ever find yourself uncertain of UV-LED words used in conversation, please ask. It will be a good test for those of us promoting the technology and will hasten the learning curve for all of us. ◗

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