UV-LED Lamps:
A Viable Alternative for UV Inkjet Applications

By Michael Beck

The power, cost and capability of ultraviolet light-emitting diode (UV-LED) lamp systems have improved to the point where they now represent a viable alternative to traditional mercury-vapor lamp curing technologies within several inkjet applications. This article will identify the advantages of the LED-based technology, as well as the engineering challenges involved in transitioning from a traditional, mercury-vapor curing system. This article will also identify some critical performance criteria that should be used when evaluating UV-LED systems.

In spite of the current economic downturn, the digital inkjet market continues to grow as end-users strive to reduce operating costs and improve the return-on-investment of capital printing equipment. When compared to traditional analog press technology, the inherent advantages of digital inkjet technology for applications requiring flexibility, customization and fast changeover are driving the growth of inkjet market share. Within the digital inkjet world, UV inkjet continues to flourish as new markets emerge. The benefits of UV inkjet—including faster print speeds; viability on non-porous substrates; chemical and resistance properties; and a positive environmental impact due to the lack of volatile organic compounds found in solvent inks—have positioned it to become a dominant technology.[1]

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One example is within the inkjet wide-format printing market in which UV is expected to experience a 16% compound annual growth rate between 2008 and 2013. Meanwhile, the aqueous and solvent printing markets are expected to be flat, or to experience negative growth during that time period.[2]

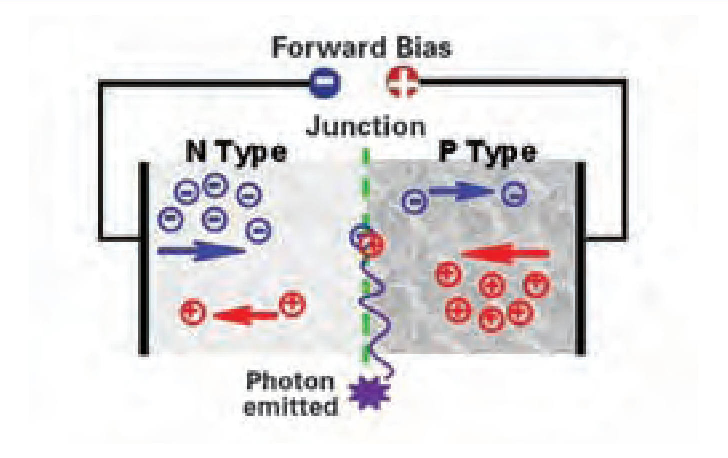
UV digital inkjet technology has been used for a number of commercial applications, ranging from the relatively low-cost, thermal inkjet (TIJ) coding and marking system to the higher speed, higher capability Piezo drop-on-demand technologies which are used in systems that range from single-pass, variable data and card printing machines to high-speed, wide-format roll or flatbed systems.

The UV-curing system most commonly used has been based on mercury-vapor lamp technology. Mercury lamp technology, whether arc or microwave driven, has existed since the late 1880s. Over time, the designs have been refined. However, the basic principles have remained the same. Typically, a mercury lamp emits a very broad spectrum of light energy (200-800nm) with specific emission peaks that are the result of selective doping that is designed to achieve a specific application objective.

UV-LED technology is relatively new, but is rapidly emerging to be a viable alternative to traditional mercury-based lamps. A UV-LED is a semiconductor device that emits photons of light in response to the application of a bias voltage across the device's p-n junction (Figure 1). The wavelength(s) of emitted light are determined by the type of materials used in the fabrication of the device. By adjusting the type and quantity of the materials used, a wide range of wavelengths are possible—including wavelengths in the ultraviolet electromagnetic spectrum.

FIGURE 1

LED concept



While UV-LEDs represent a new technology with some compelling technical advantages, it is critical to understand the fundamental differences between the two technologies in order to facilitate a successful implementation.

UV-LED vs. Traditional Mercury-based Lamps

There are some important fundamental differences between traditional Hg-based lamps and UV-LED lamp systems.

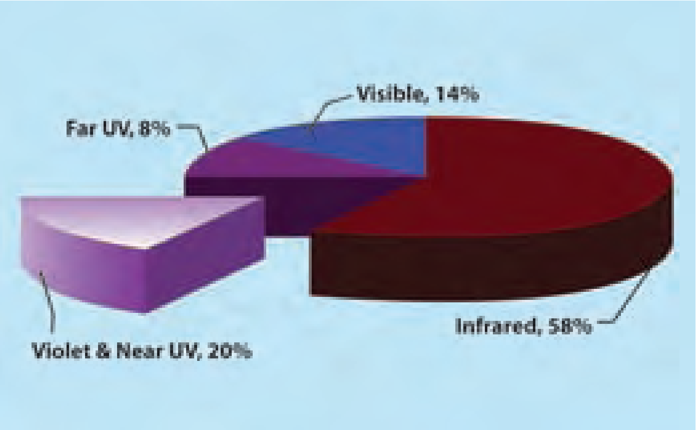
Energy Input vs. Measured UV Output

Mercury lamp systems are typically rated in terms of the input power used to drive the bulb. These ratings are usually specified in terms of "watts per inch" (WPI) or "watts per cm." This metric specifies the input, not the usable UV output of the device. For example, a 375 WPI does not produce 375 watts of UV energy; rather it consumes 375 watts per inch of bulb length. While engineers designing UV-curing systems have established baseline correlations between input power and usable UV output, there are many variables that impact the delivered power, including the quality of the UV system; reflector design and condition; and age of the bulb. All these factors force users toward active UV measurement programs to ensure that the expected UV energy is reaching the work surface.[3]

UV-LED sources are typically specified in terms of their output power—either total UV output (W) or peak irradiance-energy density (W/cm$_2$). The most practical way to specify the output is in terms of measured peak irradiance and total power output at the system emitter (or at the working surface if the application specifies a specific standoff distance). While some UV-LED systems have specified peak irradiance at the LED surface itself, such a value has

FIGURE 2

Typical mercury lamp spectral distribution



very little correlation with the actual energy delivered to the ink when system losses are considered. Until recently, the total output of UV-LED based devices was far less than the output obtained from traditional mercury-based lamps. However, recent technological advances have resulted in UV-LED lamps that can generate peak irradiance and total UV power that is similar to the output of a mercury lamp rated at 600 W/in. input power.

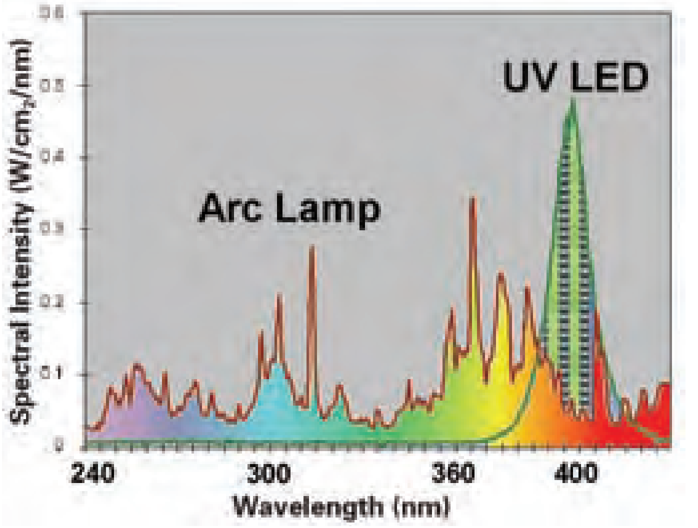
Energy Spectrum

Most mercury-vapor lamps emit a broad spectrum of light (200-800nm with specific emission patterns dependent on doping). Only approximately 20% of that spectrum is typically useful for UV curing, while over 50% of the total energy is found in the infrared wavelengths (IR). That presents a significant design challenge as it relates to the heat load on the substrate material (Figure 2).

In contrast, UV-LED systems emit a very narrow range of UV energy (typically 30-40nm). Due to limitations in the commercially available UV-LED semiconductor technology, the energy peak usually resides in the high UV-A or low UV-V spectrum (typically 350-405nm). See Figure 3.

FIGURE 3

Mercury lamp versus UV-LED spectral output



Advantages of UV-LED Lamp Technology

Lifetime

UV-LEDs have an inherently long life with UV diodes typically rated to perform for tens of thousands of operational hours. If the diode is used correctly within the lamp design (with thermal management being the most critical issue), a UV-LED lamp can be designed to outlive the typical service lifetime of the digital printer in which it is installed. (In contrast, mercury bulbs are considered a consumable item with replacement typically expected after every 1,500-2,000 hours of use.) The failure mode of an LED is most commonly related to the breakdown of the diode's p-n junction, which is usually the result of excessive heat applied to that critical region. Therefore, effective thermal management at the device level is a critical element in ensuring that LED-based lamps can perform to theoretical diode lifetimes.

Instant On/Off

Solid-state, UV-LED lamps can be switched on and off instantly (within several milliseconds). That represents a substantial design advantage because shuttering systems are not required. Furthermore, the ability to run the UV-LED system on an "as needed" basis reduces the device's overall duty cycle and can substantially extend the practical lifetime of the lamp. In contrast, mercury-based lamps typically require a warm-up period; and are often required to be kept in a standby mode and/or shuttered when not actually curing ink. Such low-power use cuts into the overall lifetime of the mercury lamp; and lamps in standby (or low powered mode) can still use substantial quantities of electrical power during the course of a year.

Heat-on-the-Substrate

Since IR makes up more than half of the total energy created by a typical mercury lamp, managing the heat load on the printed media is a reality that inkjet printer manufacturers have to face on their UV product lines. Even with the use of (1) filters and other techniques to minimize the heat delivered to the substrate and (2) media cooling systems (such as water chilled drums), the issue of heat can limit the type of materials that can be printed on. Heat can also increase the operational system costs due to hot air extraction/treatment, media cooling, etc.

In contrast, UV-LED based lamps emit a very narrow range of UV energy (typically UV-A) and zero IR energy. That's why one important driving force behind the interest in UV-LED technology is expanding the range of materials that it can be used to print on. UV energy also eliminates the need for peripheral media cooling

FIGURE 4

High-powered UV-LED lamp

systems and, potentially, expensive air extraction systems. This is not to say that a high-powered UV-LED system delivers "no heat" or is "cold technology." While the heat delivered to the print media is far less with a UV-LED system, the high UV energy levels absorbed by the ink and the media itself can result in significant heat if the lamp is left stationary over the print surface for an extended time. However, the instantaneous on/off nature of a UV-LED lamp—plus the ability to vary the output power level—minimizes any risk to temperature-sensitive media.

Power Consumption

The reduction in electrical power used to power a UV-LED system (when compared to an equivalent UV-output mercury lamp) can be substantial. Most inkjet applications can achieve a total reduction of 50-75% in the power required to drive the printer's UV system. This power savings will increase when air extraction, media cooling and the energy required to maintain the lamp's nonprinting standby mode are considered. For example, a high-powered UV-LED system—such as the Phoseon RX StarFire MAX, rated at $4W/cm_2$ over a 20x150mm emitter (Figure 4)—can output the same as or more than the total UV-A energy of a traditional 6 in., 300 W/in. mercury lamp. When both lamps are at full power, the mercury lamp would consume 1,800W compared to the 700W draw of the UV-LED lamp—that's a 61% reduction in peak energy consumption. The reduction in total power required for the UV-curing system has cost implications to the end-user, as well as design implications for the inkjet system engineer.

Environment and Safety

While traditional, mercury-based UV lamps have been widely deployed and accepted in a wide variety of industrial and printing applications, the inkjet printer manufacturer has to carefully design their system to ensure that no operator or person near the UV-curing system is exposed to potentially dangerous UV wavelengths or heat. This consideration has an impact on the total size, weight and portability of a traditional, mercury-based UV system that typically has to be fully enclosed and shielded so that no human can see or touch the enclosure while the lamp is in operation. In contrast, UV-LED systems emit no UV-B or UV-C wavelengths that are inherently more dangerous to the human eye. Also, most UV-LED designs do not transmit substantial heat to the lamp enclosure itself, thus reducing the design constraints placed on the inkjet system designer. Since mercury is not used within an LED system and no ozone is created as a byproduct of the narrow-band UV-A energy, LED-based systems are inherently environmentally friendly.

Challenges in Transitioning to UV-LED

While UV-LEDs now approach or even exceed traditional mercury lamp power, and also offer substantial benefits, there are still several critical limitations that impact the transition to solid-state UV lamps that should be fully understood.

Ink Formulation

In general, UV-LED lamps are not suitable for "drop-in" replacement of existing mercury-based lamp systems. Nearly all UV-ink formulations have been optimized to react with the spectral characteristics of mercury lamps in an array of doping configurations. The commonly used free radical UV chemistry uses photoinitiators that are formulated to react with the multiple spectral peaks output by mercury lamps. Transitioning from a polychromatic mercury vapor lamp to a near-monochromatic UV-LED lamp almost always requires that the ink be adjusted and optimized in order to achieve the proper curing and ink properties.

Surface Curing

The primary challenge in optimizing ink for UV-LED is effective surface curing, which can be hindered by oxygen inhibition and result in an improperly cured or "tacky" ink surface. Ink formulations that are optimized for mercury-vapor UV sources take advantage of the lower UV-B and UV-C wavelengths to achieve effective surface curing. Ink formulations created for UV-LEDs achieve effective surface curing via the addition of compounds that can consume the oxygen (such as amines or aminoacrylates[4]) or, in some cases, by printing in an inert (nitrogen) environment. Overcoming surface curing issues has been a fundamental issue for UV-inkjet ink suppliers and formulators. However, the combination of much higher total UV-A energy levels now available and oxygen-consuming additives has resulted in commercially available multicolor ink sets that are optimized for UV-LED lamps.

UV-LED Lamp Thermal Management

While UV-LED lamps do not generate the "large" heat issues related to mercury-vapor lamps, the thermal management of UV-LED diodes is a critical factor in being able to achieve the power levels and lamp lifetime required for digital inkjet applications. Various heat management techniques have been developed, including active air and water-cooled systems. Water is inherently more efficient than air cooling and can result in higher overall LED lamp power. Such designs require a peripheral water cooling system—either a radiator-based water circulator or recirculating chiller. Since the UV lamps are stationary on many single-pass and narrow-web digital inkjet printers, water cooling is not a substantial design limitation. However, since wide-format printers utilize UV-curing lamps (typically two) on the carriage containing the print heads, water cooling presents additional design challenges. While air-cooled LED systems are generally preferable for wide-format printing applications, several designs have been realized that incorporate water-cooled, UV-LED lamps. In those cases, the higher UV power and faster cure rates on heat-sensitive media were more critical than the additional complexity and expense of a recirculating chiller and tubing/plumbing.

UV-LED Lamp Performance Criteria

As UV-LED technology continues to emerge and as new suppliers enter the market, it's important for the potential inkjet printer manufacturer to understand and appreciate the critical lamp characteristics. The section below suggests a baseline criteria in comparing UV-LED lamps.

Wavelength

The wavelength of the diodes used by a UV-LED lamp has implications on curing performance, power and lamp lifetime. Ink formulators initially requested that UV-LED lamps emit a peak around 365nm—a wavelength that matched one peak within existing ink systems. As an alternative, lamps have been developed around a different die set with a peak of 395nm (or 405nm). UV-LED lamps designed around 395nm diodes have several potential advantages, including cost, availability and a more robust structure that can result in higher UV-power outputs.

Recent research has indicated that peak irradiance and total UV-A power delivered are more important than a precise wavelength match on inks developed to cure in the UV-A region. The summary finding is that, "The peak intensity and total energy of a UV-LED source in the UV-A region is relatively more important for cure performance than the specific peak wavelength of the UV-LED source in the UV-A region (365nm vs. 395nm). In the end, energy trumps wavelength in terms of the reaction—at least when the wavelength ranges are relatively close together in the spectrum."[5]

Peak Irradiance and Dose: Total Power Delivered

Peak irradiance is an important metric since intensity is required to initiate the polymerization of the ink. Higher peak irradiance results in a more aggressive polymerization mechanism that is important in obtaining full cure; helping to overcome oxygen inhibition at the

FIGURE 5

UV-LED peak intensity versus total power

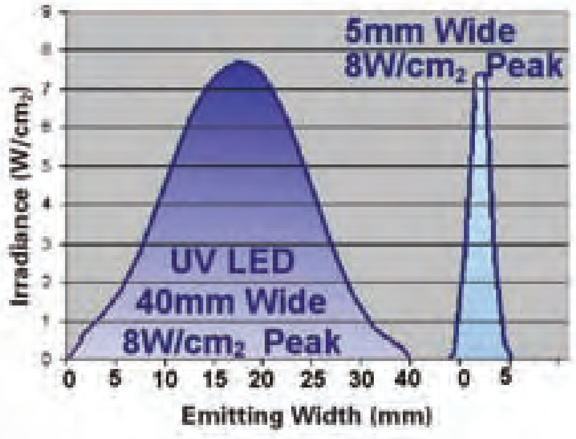


Figure 6

UV-LED pinning lamp

surface; and achieving the required cure rate. However, peak irradiance is only one important variable. Optics and reflector schemes can focus energy to obtain high peak irradiance over a relatively small area, often at the expense of total power delivered to the ink due to optical losses. Research indicates that total power delivered to the ink is a critical variable in achieving cure rates that are acceptable to the inkjet printing market.[5] Figure 5 illustrates the difference between a high peak intensity achieved optically at the expense of total dose delivered.

Uniformity

Uniformity of UV energy can be an important characteristic for many inkjet applications; particularly those targeting graphic arts applications. Uneven UV energy emission patterns, hot spots or gaps in the UV output can have severe negative effects on the quality of the printed material, including partially cured areas, as well as gloss and color banding. Characterizing the uniformity of a UV-LED lamp should be an important consideration when comparing lamp designs.

Figure 7

Narrow web flexographic press using UV-LED

UV-LED Ink-Jet Applications

Pinning

UV-LED lamps can be very effective for a technique known as “pinning” in which the jetting ink is partially (not fully) cured after each color deposition. The small size of a UV-LED pinning system allows it to be mounted in between the inkjet heads (Figure 6). Pinning can result in a noticeable improvement in image print quality because the jetting ink is effectively frozen in place until the final curing is achieved.

Full-Cure Systems

A growing number of commercially available inkjet systems have successfully incorporated UV-LED lamps for full cure. At the low end of the price scale are single-pass TIJ-based printing systems that are typically designed for addressing, labeling or variable/barcode printing applications. These applications find UV-LED attractive due to the relatively small size and easy integration of LED-based lamps compared to traditional mercury-based systems. Due to cost constraints, TIJ-based inkjet systems require small, affordable air cooled UV-LED systems that offer acceptable cure rates on a variety of print media.

At higher price points, faster and more capable multicolor, piezo-type drop-on-demand inkjet systems are used. Within this marketplace, heat-sensitive media, power consumption and environmental factors are the driving forces behind the acceptance of UV-LED technology (Figure 7). Wide-format printing is another market space in which UV-LED based systems will play an important role. Expanding printing options on heat-sensitive media and a more favorable cost of ownership/operation are the drivers in this application.

Future of UV-LED Lamps

UV-LED will continue to gain acceptance as the output increases and the initial investment costs decrease. Over the past two years, the price per watt of UV-LED energy has decreased dramatically. As more ink/chemistry suppliers are pushed by their customers to develop UV-LED optimized materials, additional applications will adopt this technology. Recently, UV-LED has been expanded to traditional analog printing—one such press was unveiled this year and it included an optimized flexographic ink set.

Conclusions

UV-curing applications in the digital inkjet world are growing. Within the UV inkjet space, UV-LED sources are rapidly emerging because recent lamp designs have met the intensity/total power requirements and they feature several inherent design advantages, including long life, ease-of-integration, instant on/off, reduced power consumption and dramatically reduced heat loading on the print media. As a result, UV-LED devices are now a viable alternative for many UV-inkjet applications. While UV-LED offers some compelling advantages, there are some important engineering considerations—most notably ink formulation. However, ink suppliers continue to innovate, develop and release ink formulations that are optimized for the relatively narrow, yet intense, spectrum of high-powered UV-LED lamps. ◗

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