The first production LED-powered projector debuted in 2005, and a number of projectors with output of 5 to 15 lumens from various manufacturers followed. These new smaller projectors could easily fit into a briefcase but were still too large to fit into a jacket pocket (Reference 1). The units, weighing 0.21 to 1 kg, became known as pico projectors and could display an image large enough for a small audience in a dark room.

In 2007, 3M began shipping the MP1xx series of pico projectors, ranging from the MP120, capable of 12-lumen output, to the MP180, with 30-lumen output. All of these stand-alone projectors included built-in batteries capable of two hours of runtime and of displaying still images and videos stored in onboard memory or from an external source.

Subsequently, other pico projectors emerged. These units were embedded in handheld appliances, such as digital still cameras, cell phones, and camcorders. To date, few cell phones with built-in projectors are on the market due to the cost, size, and battery drain that the addition of a projector causes.

A typical pico-projector design comprises an LED light source; collection optics, which direct the light from the LED to an imager; an imager, typically a DMD (digital micromirror device) or an LCOS (liquid-crystal-on-silicon) device, which accepts digital-display signals to shutter the LED light and direct it to the projection optics; output or projection optics, which project the display image on the screen and also permit functions such as focusing of the screen image; and control electronics, including the LED drivers, interfacing circuits, and the video and graphics processor (Figure 1).
Design challenges

For many LED applications, the total number of extracted lumens, or luminous flux, is the most important parameter. For projection, the important parameter is not the total number but the usable number of LED lumens—that is, those that can be guided through the optical system. For a pico-projector module embedded in a mobile appliance, the available electrical power is limited to a fixed value to ensure achieving the expected battery-operation time. The figure of merit, therefore, is the projector efficacy in lumens per watt. The LED source must meet the needs of the chip and package efficiency and match those of the projector’s optical system.

Imagers’ panel types, sizes, and illumination architectures all require different types of LEDs for achieving maximum projector efficacy. Osram Opto Semiconductors has introduced LED chips with enhanced optocoupling features. These chips employ ThinFilm and ThinGaN chip technologies and have high inherent efficacies and surface-emitting properties. Red ThinFilm and green and blue ThinGaN chips use AlInGaP (aluminum-gallium-indium phosphide) and InGaN (indium-gallium nitride), respectively. Dominant wavelengths of 617, 525, and 460 nm project the spectral emission for red, green, and blue, respectively (Figure 2).
Figure 3 shows the relative efficacy, normalized to 100% at 350 mA/mm², versus current density for ThinFilm and ThinGaN chips. The figure illustrates the relative efficacies in lumens per watt for standard chip sizes: 500 microns, 750 microns, and 1 mm, or 20, 30, and 40 mil, respectively. It shows that efficacies at 350 mA decrease with increasing current density. This so-called current droop is stronger for ThinGaN than for ThinFilm chips. Therefore, you achieve higher efficacy by selecting the maximum LED chip size.

Each projection optical system has a maximum usable light-emitting area of the LED. Beyond this maximum area, you cannot guide the additional light through the optical system. This quantity is useful for calculating the usable amount of light that can be guided through the projector optics system (Reference 2). It determines the maximum usable emitting area of the light source as it quantifies the spatial and angular extent of a light beam. The étendue of an LED is a property of pencils of rays in an optical system, which characterizes how spread out light is in area and angle: \( E = N^2 A \Omega \), where \( N \) is the refractive index of the medium, \( A \) is the emission area, and \( \Omega \) is the projected solid angle.

In an ideal optical system, the étendue is a constant throughout the optical path. You can neither decrease the étendue nor increase the luminance. The optical system’s étendue—that is, the imager panel’s size and the acceptance angle of the optical system—limits the LED’s étendue:

\[
E_{\text{LED}} \leq E_{\text{SYSTEM}} \quad \text{and} \\
N^2 A_{\text{LED}} \sin^2 \theta_{\text{LED}} \leq A_{\text{P}} \sin^2 \theta_{\text{SYSTEM}}
\]

where \( N \) is the refractive index of the LED encapsulation, \( A_{\text{LED}} \) is the LED’s emitting surface area, \( \theta_{\text{LED}} \) is the half-angle of the emission cone, \( A_{\text{P}} \) is the active area of the imager panel, and \( \theta_{\text{SYSTEM}} \) is the acceptance half-angle of the system.

The acceptance angle of the imager’s panel or the F-stop number of the projection lens can limit the acceptance angle of the optical system. As the equation shows, the LED’s emitting area is limited to a maximum usable area. If the LED area exceeds this limit, some fraction of light is lost because it cannot be guided through the optical system.

The surface-emitting properties of ThinFilm and ThinGaN LEDs without the use of reflectors provide the highest luminance at the lowest étendue.

You can achieve the best chip size for system efficacy if the LED’s étendue equals the system étendue, as the following equation shows:
The half-angle, $\theta_{\text{LED}}$, of the emission cone of a surface-emitting LED is 90°. A secondary optical system, such as a lens outside the LED package, is used to collect the light—typically, within a 70° or smaller cone. Therefore, the collection angle influences the optimum chip size. A narrower collection angle allows a larger usable chip area (Reference 3).

As costs increase with imager size, you should try to use the smallest imager that meets the performance requirements. Because the LED’s cost also increases proportionally with the chip area, the goal is to maximize the chip area for chip efficacy but not to exceed the system étendue limit; doing so would waste the excess chip area.

Several small DMD and LCOS imager panels are available for embedded systems. Table 1 lists the parameters of four imager panels and the optimum LED chip size.

<table>
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<tr>
<th>TABLE 1 IMAGER PANELS AND LED SIZE</th>
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<tr>
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<tr>
<td>Diagonal size (in.)</td>
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<td>Acceptance angle (°)</td>
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<td>Étendue (mm²)</td>
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<td>Optimum chip size (mm)</td>
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Illumination types

The four-chip LED products containing RGGB (red/green/green/blue) are typically for one-channel illumination (Figure 4). The two green chips help to compensate for the lower efficiency of the green LED; green contributes more than 65% of the white-screen lumens. Although the one-channel approach eliminates the need for combining color beams, an optics element, such as a lens array or a mixing rod, is necessary for achieving color uniformity across the whole imager panel (Reference 4). The screen lumens are limited because the maximum emitting area contains all three colors. Therefore, designers use this approach mainly for low brightness and low cost due to component simplicity (Reference 5).

The most straightforward illumination architecture is a three-channel configuration in which dichroic filters combine the three beams of colors (Figure 5). This approach can use the maximum emitting area for each color because it superimposes the three areas. Three-channel illumination offers the highest system throughput but costs more and requires more space due to the need for additional hardware.
Combining two colors within one LED device and using a second device for the remaining color is the basis for a two-channel configuration. This approach takes up less space and costs less than a three-channel approach and offers higher throughput than a one-channel approach.

**Figure 6** shows the configuration of green and red/blue, combining red and blue in one device, with green in a separate package. It is usually beneficial to use a 1- or 2-mm² chip for green, which is larger than that for the red/blue chip, to compensate for the lower efficiency of the green LED.

**Converted green**

Due to the need for more than 65% of the green flux component to generate white light, Osram has developed converted green by using a blue-LED pump to excite green-ceramic-based phosphor. This combination results in 90% more green lumens with wider spectrum than native true green (**Figure 7**). The built-in dichroics in a two- or three-channel architecture remove the overlapping color spectrum, resulting in approximately 40% higher white-lumen output (**Figure 8**).
Drive electronics

Using a multichannel single-driver chip yields cost and space savings. In a color-sequential system, generally only one color is turned on at any time. For this reason, some drivers can effect additional savings with the use of shared circuitry for the three colors.

However, it is important to make two allowances in the selection of the LED driver. First, make sure that the chip can accommodate the difference in forward voltage between the red chip—typically, 2.5V—and that of the blue and green chips—typically, 3.6V. Second, overlapping two or more colors can increase projector output in some projector designs.

LEDs are excellent light sources for pico projection due to their compact size and high lumen output. The selection of an optimal LED for projector efficacy takes into account system size, imager type and size, brightness requirements, and power consumption. The use of different chip and package sizes enables illumination architectures, such as one-, two-, and three-channel illumination, depending again on the same factors as in LED selection.

You can achieve optical efficiency of more than 90% for three-channel architectures and more than 80% for two-channel architectures with the appropriate choice of LED and imager. In addition to the efficacy, projector engine size and cost are also key variables when selecting an LED for pico projection.

Dell recently launched the M110 ultramobile projector, which outputs 300 lumens using a three-channel architecture and converted green. Assuming that LEDs follow Moore’s Law, you can expect further gains in brightness and lower cost in the coming years. Projectors embedded in cell phones will be more common, and pico projectors will be bright enough for serious business presentations without the need to dim room lighting.

References

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Authors’ biographies
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