Traditional light bulbs burn up a great deal of energy. A full 22% of the total annual electrical consumption in the United States—about 6 quadrillion BTUs—goes to lighting homes, schools, and businesses. Incandescent lamps represent 42% of this demand. For all that power, though, we only get about 12 to 15 lm/W, which does not represent a very efficient system.

Theoretical limit for generating good quality white light from LEDs is about 330 lm/W. With further improvements in chip-level internal and external quantum efficiencies and optimized package designs, we can realize a wall-plug efficiency of 70%. This would result in a 155 lm/W solid-state light source, which is far superior in performance to any commercially available source of white light available today (see figure 1). In order to reach this performance level and replace Thomas Edison’s bulbs with white-light LEDs, the design of...
the solid-state light source needs to be optimized for energy efficiency, cost, and total light output at the higher power levels.

We can generate white light from an LED in two ways: We can coat a single chip with one or more phosphors, or we can mix white light from individual LEDs that emit different colors, such as red, green, and blue. A challenge for the latter approach is the poor color-point stability, which would require the use of special controller circuitry to maintain the color balance. In contrast, phosphor-based white LEDs are rugged, compact devices that can be manufactured to specific color requirements and that function more like traditional light bulbs.

The lighting industry currently mass produces a white solid-state lamp based on a blue LED chip with dominant wavelengths between 440 and 470 nm, combined with a yellow broadband phosphor, usually cerium-doped yttrium aluminum garnet (Ce:YAG). The phosphor converts a major fraction of the blue excitation light from the chip to light between the cyan and the red regions of the spectrum. The human eye perceives the resultant optical mixture as white light. We can tune the lamp's correlated color temperature between 4000 and 8000K by adjusting the phosphor loading. To achieve a lower color temperature—for example, to create lamps that mimic the color temperature of incandescent light sources—we need to develop a phosphor that emits more strongly in the red region of the spectrum.

Recent advances in LED chip technology have made available near-UV devices with dominant wavelengths below 410 nm. A blend of at least two phosphors, similar to the mixture used in mercury fluorescent lamps, converts the near-UV output to white light. Manufacturers can achieve color points over a very broad range, often by merely adjusting the ratio of the phosphor constituents. For instance, our group developed a blend of blue, cyan, and orange phosphors that covers the entire range from 2000 to 8000K. An added advantage of this approach is that the color point stability of the UV chip system is superior to that of the blue chip. The color point sensitivity to variation in chip wavelength is inherently lower in the near-UV region because the human eye is less sensitive to wavelength variation in the 400 to 410 nm range when compared to the 450 to 470 nm range.

Achieving Performance

An important characteristic of any white light is its color rendering, a metric that essentially describes how a source will affect the apparent color of objects. Phosphor-based white LEDs typically have a color rendering index (CRI) of about 70 to 82, a fair value similar to that of standard linear fluorescent lamps; the CRI for incandescent lamps is 95+. Fluorescent CRIs are considered sufficient for most general illumination applications, although certain applications such as specific types of retail lighting may need CRIs above 95. Developing new phosphors will let manufacturers obtain higher values.

We can define an overall figure of merit for white LED efficiency as

\[
\text{FOM} = \eta_{\text{WP}} \eta_{\text{lum}} \eta_{\text{SS}}
\]

where \( \eta_{\text{WP}} \) is the wall-plug efficiency, defined as the fraction of input electrical power extracted as optical output power; \( \eta_{\text{lum}} \) is the luminous efficacy, defined as the photopically weighted output divided by the radiometric optical output power; and \( \eta_{\text{SS}} \) is the Stokes-shift efficiency, which corresponds to the energy efficiency for the conversion of light from the chip to longer wavelengths. The conversion of a 450-nm photon generated by the LED chip to a 600-nm photon via the phosphor, for example, implies a Stokes-shift efficiency of 450/600 = 0.75, a 25% loss of its initial energy.

It turns out that the white LEDs are most efficient...
around 405 nm, due primarily to the peak in wall-plug efficiency observed near that wavelength. For appropriately chosen phosphors, luminous efficacy does not change considerably with wavelength, and the Stokes shift improves monotonically as the chip wavelength increases. In relative terms, the 405-nm system is capable of 40% higher light output than the 470-nm system, which in turn is capable of 20% higher output than the 380-nm system.

**Packaged Goods**

LEDs are spontaneous emitters, so the photons generated in the active region are emitted isotropically in solid cones. To reduce the absorption of emitted photons within the semiconductor material or the package, we can use various techniques that improve the light extraction efficiencies. An interface medium with a refractive index of $n_2$, for example, Different chip geometries improve the light extraction from the sidewalls of the semiconductor die.

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**Figure 2**

A thermal package currently being developed has thermal resistance near 10°C/W.

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LEDs have two primary areas of packaging that play a role in extraction efficiency. The first concerns the LED die and its immediate package, often called a Level 1 (L1) device. At this level, a properly attached die allows electrical power to flow through the device and generates heat to flow out to the environment. The die and related elements are in turn held together by a plastic package that also contains an encapsulant, which protects the chip and shapes the light distribution.

It is critical to remove the heat generated by the LED from the device. LEDs are considered low-power devices, as they typically dissipate only up to 1 W of power. If the thermal path is poor, however, the temperature of the die and L1 device will be quite high. In general, most devices are limited to a die junction temperature ($T_j$) of 125°C, due to the phase transition temperature of the encapsulant material. Go beyond that point and package failures become common. In addition, LED lifetime is inversely proportional to junction temperature, and we can only achieve long life (25,000 to 50,000 hours) if we keep $T_j$ below 75°C. In a typical lighting environment with an ambient temperature $T_a$ of 25°C, the maximum temperature rise allowable in the die is 50°C above $T_a$. The corresponding maximum thermal resistance from die junction to ambient for a 1-W class device, therefore, is 50°C/W; thermal resistance is an impedance concept similar to Ohm's Law.

Early LED packaging, for devices originally meant as indicators rather than high-power illuminators, couldn't handle these kinds of requirements. The then-standard 5-mm or T-1 3/4 package has a thermal resistance of around 300°C/W, making it unsuitable for today's high-power emitters. As a result, several manufacturers have developed LED power packages with much lower thermal resistances, near 10°C/W (see figure 2).

**The Big Picture**

System integrators must address the same thermal management issues at the system level as at the chip level. Unlike traditional filament-based bulbs that radiate away 90% of waste heat, LEDs must be conductively cooled, which requires pulling heat away from the L1 device and passing that heat to the ambient air. With these constraints, the system must now incorporate metals and other materials that conduct heat well, avoid large contact resistances in the thermal path that can block heat transfer, and provide adequate surface area to allow convection to remove heat to the surrounding air.

Much of the heat moves through the bulk of the device, and proper design of this convection path is typically the most critical. In a system, natural or free convection often represents 70% of the thermal resistance of the entire thermal path. Fans and other air movers are extremely helpful in reducing this figure, but they add cost and decrease system reliability, so we normally exclude them. Ultimately, most systems use natural convection and must incorporate some structure with large surface area—a lighting fixture or a heat sink, for example—to keep the structure temperature, and hence $T_j$, low.

To achieve the optimal performance and system lifetime, an LED lighting designer must carefully balance not only light output design and fixture design, but also thermal path design.

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