

# **Beyond the Limitations of Today's LED Packages: Optimizing High Brightness LED Performance by a Comprehensive Systems Design Approach**

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## **ABSTRACT**

Critical requirements including high brightness, high color rendering, and high wall plug efficiency for the most demanding LED applications such as surgical illumination and industrial and dental sealant curing are difficult to meet with the limitations posed by commercially available LED packages.

The importance of optimizing an illumination system from the system-level perspective is presented. It is necessary to integrate efficient die, electrical drive conditions, heat dissipation, LED out-coupling optics and auxiliary optics. It is not sufficient to collect the maximum amount of light from an LED package; the light must be captured into a minimum aperture while maintaining maximal brightness. Commercially available LED packages, including the recently available 1 and 5 Watt emitters, suffer by varying degrees, in their applicability to today's most demanding applications. An optimized LED package is described that outperforms commercially available packages. Specific medical, commercial and industrial LED applications are described that can meet many of the most demanding requirements with today's technology.

**Keywords:** LED, high brightness LED's, nonimaging concentrator, compound parabolic concentrator, CPC

## **1. INTRODUCTION**

The use of LEDs for high brightness applications has been enabled by recent efficiency improvements in commercially available LED die. Many applications are difficult to realize, however, due to the limitations posed by commercially available packaged LEDs. The premise of this paper is that the product specifications should drive the package design, thus it is necessary to examine all the design parameters that are required to optimize LED package performance. Section 2 begins with a description of a generalized LED illumination system as a point of reference. The section also discusses design considerations including optical, electrical, thermal, and mechanical, emphasizing the need to consider manufacturability, cost, and reliability throughout the design optimization process. An optimized LED package is presented along with a novel scanning LED technique that promises to open up even more applications that are currently limited to high intensity discharge lamps. Section 3 presents a few applications of the optimized LED packaging technology.

## **2. OPTIMIZING LED PACKAGE PERFORMANCE**

### **2.1 System-level flow down**

Commercially available LED packages work adequately for many applications. For the most demanding applications, however, the commercially available packages may pose severe limitations on the system performance, cost, size, and manufacturability. Figure 1 represents a system-level flow down of the process for deriving an optimized LED package design. The top-level product specifications should drive the design. The optical, electrical, thermal, and mechanical analyses must be refined in an iterative process with consideration for manufacturability, reliability, performance, and cost to arrive at an optimized LED package.

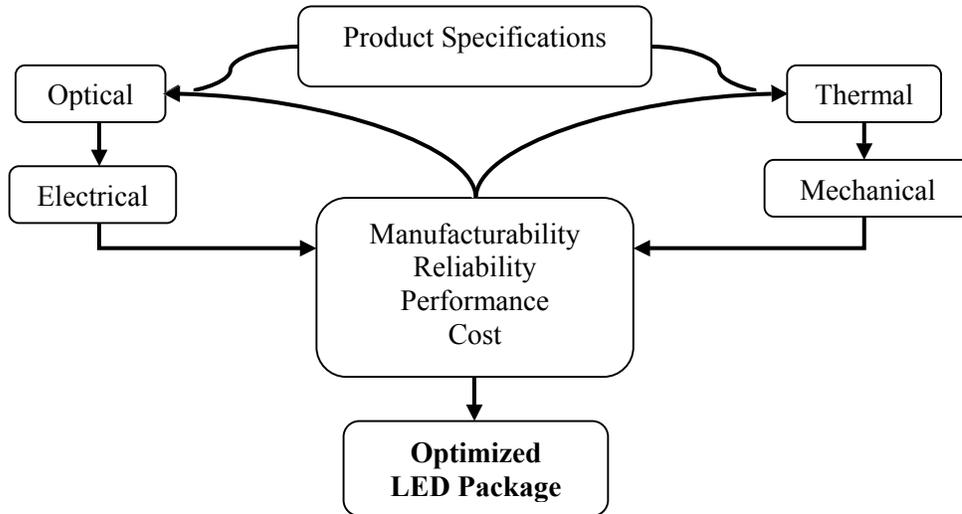


Figure 1. The system-level flow down from the product specifications to an optimized LED package design is shown.

## 2.2 Principle components of LED illumination system

The principle components of a generalized illumination system are depicted in Figure 2. The LED die or die array are attached to a header characterized by high thermal conductivity. The header must be appropriately cooled by attachment to some form of heat sink, which in turn can be cooled by conduction, convection, or radiation. Heat sink performance is

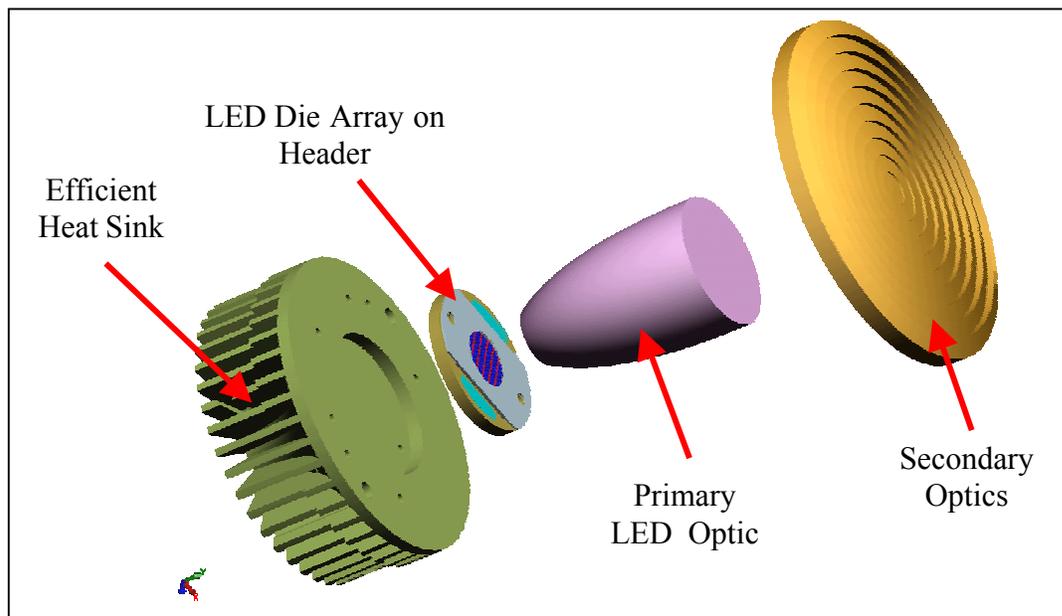


Figure 2. The principle components of an LED illumination system are shown.

critical to optimal performance of the LED system. The importance of good thermal design is often overlooked [1]. Perhaps the most neglected aspect of many LED illumination systems is the efficient coupling of the LED output to the target illumination area. The primary LED optic shown in Figure 2 is a highly efficient compound parabolic concentrator (CPC) belonging to a general class of nonimaging optics (patent pending). The optimal form of the primary optic depends on the required illumination pattern. For example, in the case where a Lambertian distribution is required over a hemisphere, the optimal primary optic is likely to be a substantially hemispherical dome with the LED near the center of curvature and immersed in an index-matched medium. This type of system, however, is not considered to be a high brightness system design and is not relevant to this discussion. In some cases, the primary optic is all that is required to meet the product specifications. This would be the case, for example, for a fiber optic illuminator, for which the CPC is particularly well suited as will be described in Section 2.3.2, below. In some cases supplementary secondary optics, represented here by a Fresnel lens element, are required to achieve the desired illumination pattern. Various forms of secondary optics are discussed in Section 2.3.3.

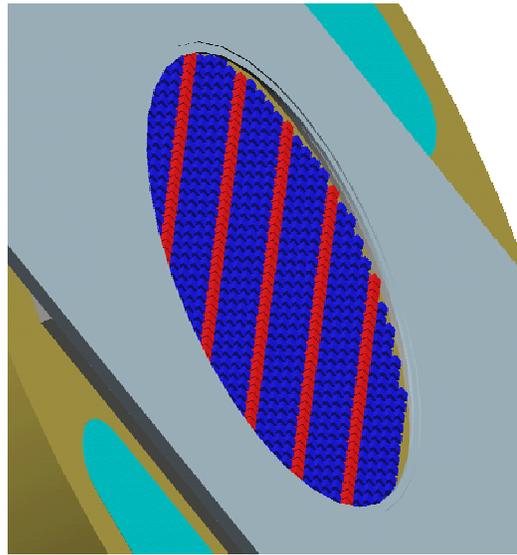


Figure 3. A close up view of alternating blue and red die are shown in an array. The addition of a yellow phosphor results in a color rendering index exceeding 90.

Figure 3 represents a close up view of an LED array comprised of alternating rows of blue and red die suitable for a high quality white light system by the addition of a top layer of phosphor. Such an LED array is capable of producing white light with a color rendering index (CRI) in excess of 90.

### 2.3 Design considerations

The following section discusses the critical concepts required to derive an optimized LED package. It is critical to the success of an optimized LED package to take proper account of all aspects of the design outlined in Figure 1 and expounded upon in the following sections.

Although there are not specific sections dedicated to cost and reliability, these attributes of an LED package are of great importance and must be considered throughout the design process. Some people may argue that it is not cost effective to design a custom package. There are certainly cases where this will be true, but for illumination applications with demanding performance requirements and of sufficient volume, we would argue that in most cases, the optimized package is the best solution.

$$H (n \sin\theta) = \text{Optical Invariant} = \text{Constant}$$

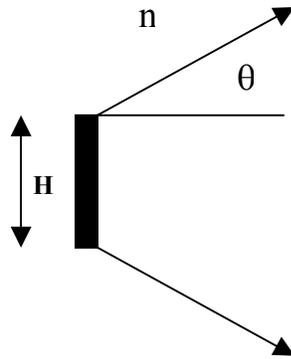


Figure 4. Conservation of radiance is proportional to the square of the invariant and is alternatively known as the brightness theorem.

### 2.3.1 Conservation of radiance

The concept of “Conservation of Radiance” or etendue is very often misunderstood in the field of optics and particularly in regard to LED illumination design. Figure 4 shows a representative emitting surface, indicated by the black box, which subtends an angular extent given by  $2\theta$  and a linear dimension of  $H$ . The optical invariant states that the product of the linear dimension of a source and the product of the index of refraction of the medium and the sine of the half angle is conserved through an optical system. That is, at any downstream position or optical element, this quantity is conserved. The square of the invariant is also conserved and is proportional to the radiance or brightness throughout the system. The conservation of radiance is alternatively known as the brightness theorem.

The optical invariant can be used to determine the output aperture for an idealized optical concentrator for a given LED die or die array. For example, if an LED array is characterized by a unit diameter, the optical invariant results in an output diameter of 4.39 units, assuming an index of refraction of 1.5 and an output half angle of 20 degrees.

### 2.3.2 Nonimaging concentrator

A nonimaging concentrator such as the compound parabolic concentrator shown in Figure 5 comes within about 4% of the performance of an ideal concentrator and is ideally suited for use with LED die or LED die arrays (patent pending). The output of an LED approximates a Lambertian source for many LED die, falling off as approximately the cosine of the angle between the LED surface normal and the direction of the viewer. The CPC takes the form of a shifted and tilted parabola of revolution in accordance with the edge ray principle [2]. Of the radiation entering its input aperture, 96% falls within the angle and exit aperture diameter dictated by the optical invariant. Thus, the CPC is nearly an ideal concentrator and well suited for LED applications.

Figure 6 illustrates the optical invariant for which a unit input aperture for the top CPC results in a proportionally smaller output aperture, but larger exit numerical aperture relative to that of the bottom CPC as indicated by the table to the right.

The near field output of the CPC, assuming a uniformly filled input, is substantially uniform and ideally suited for such applications as interfacing to fiber optic bundles. The far field is also very uniform as indicated in Figure 7. The sharp fall off in intensity at the limiting design angle aids in an efficient system-level design. The uniform far field makes the CPC-coupled LED ideally suited for general illumination applications as well. Several applications for this package geometry will be introduced in Section 3.

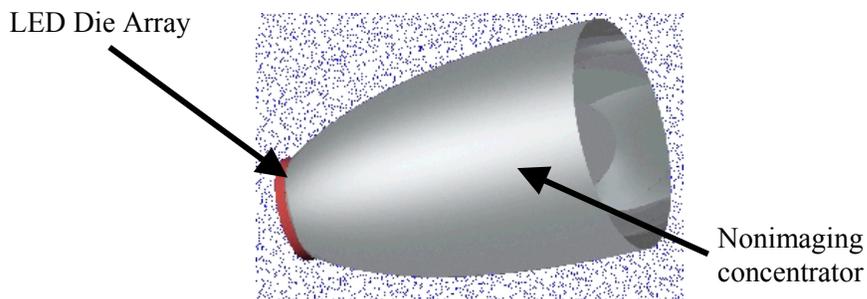


Figure 5. An LED die array is shown that fills the input aperture of a nonimaging concentrator.

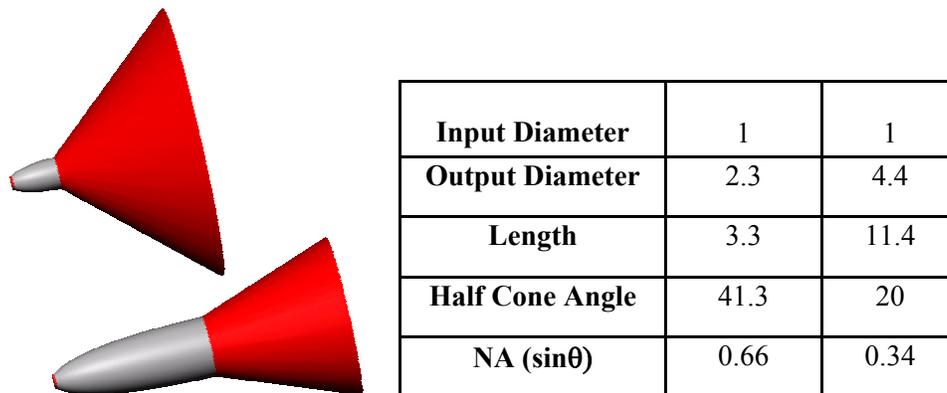


Figure 6. The two compound parabolic concentrators (CPC's) have identical input apertures, but different output diameters and angular extents in accordance with the optical invariant.

## Far Field Intensity of 7.5 W Emitter

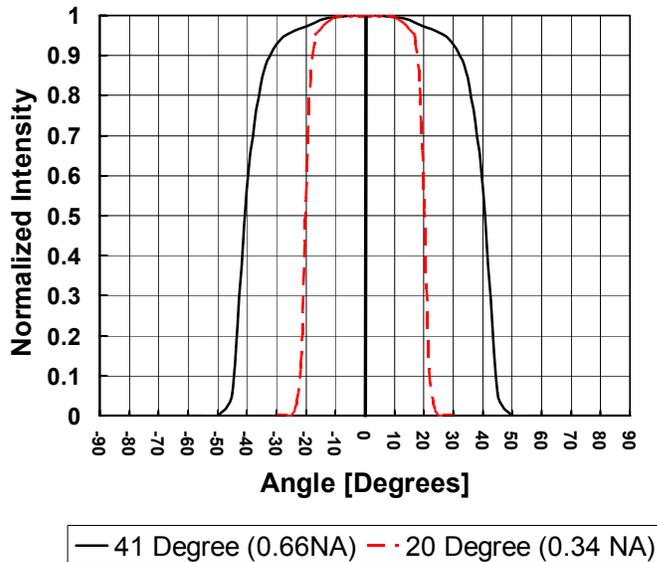


Figure 7. The far field intensity distribution for an LED with two different CPC output angles is shown.

### 2.3.3 Secondary optics

Secondary optics design forms include but are not limited to light pipes, refractive, reflective, diffractive, faceted, imaging and non-imaging forms. Excellent software tools are available for non-sequential ray trace modeling and iterative optimization of LED illumination systems such as TRACEPRO<sup>®</sup>, LightTools<sup>®</sup>, and ASAP<sup>®</sup>. The use of solid modeling CAD software such as SolidWorks<sup>®</sup> and ProEngineer<sup>®</sup> increases modeling efficiency by allowing changes to be readily made to complex design forms. Solid geometry can be imported from these CAD tools directly into the optical programs.

### 2.3.4 Electrical

There are many electrical considerations and trade-offs that must be addressed, including the current and voltage available to power the LED die or die array. The concept of wall plug efficiency is useful for describing the efficiency of an LED system and is defined as the ratio of the radiometric output power to the electrical input power expressed as a percentage. The authors generally favor this radiometric method of describing LED efficiency over the photometric parameter of luminous efficiency due to the fact that wall plug efficiency is inherently normalized. Luminous efficiency is defined as the number of lumens of output per Watt of electrical input power. The theoretical maximum luminous efficiency occurs at a wavelength of 555 nm governed by the daylight response of the human eye and has a value of 683 lumens per Watt. Luminous efficiency is, however, a good metric to compare white LED illumination with other more standard methods such as tungsten or fluorescent lamps.

Wall plug efficiency is not a constant for LEDs, but decreases with increasing current density. This fact gives the CPC-coupled LED a distinct advantage for many applications over standard packages, in that for a given output aperture and

half angle, it maximizes the number of die that can be used. Thus for a given optical output power, the current density can be minimized, thereby maximizing wall plug efficiency. This is of particular advantage for portable battery operated systems.

Another electrical consideration for which there has been considerable debate is whether to drive an LED die array in series or in parallel. The choice may be driven by the forward voltage requirements of the die and the voltage available from the power supply. Many systems use a combination of serial and parallel drive. LED die are often binned according to output power at a standard drive current, such as 20 mA. At this drive current, however, the forward voltages of a group of binned die may vary, which effectively means the wall plug efficiency varies from die to die. This may result in intensity variations over the LED die array when driven in parallel. It may seem that it would be desirable to drive an array in series for this reason, but that is not very practical given the electrode geometry of typical die. Additionally, if one of the die should fail for any reason, it would cause failure of the entire array. In practice the effect of the variation in forward voltage is not that significant when used with the CPC as its nonimaging nature tends to homogenize the output.

There are two common means of attaching the die to the header, conductive epoxy and eutectic alloy. Historically, most LED die were attached by means of conductive epoxy, however, the improved thermal performance of the eutectic attachment has made this approach become more prevalent.

There are also two common wire bonding techniques, ball bonding and wedge bonding. Ball bonding generally results in greater pull strengths, but wedge bonding lends itself better to stitching a series of die together, so the choice of technique is often dictated by the array geometry.

Recently, several vendors have offered manufacturing services for “chip on board” headers that incorporate thin dielectric layers laminated to ceramic or metal boards of high thermal conductivity on which electrical traces can be fabricated. These boards can even be multi-layered by incorporating additional dielectric layers. This technology can significantly reduce package complexity, size, and cost with perhaps the only penalty being a negligible increase in thermal impedance.

### 2.3.5 Thermal

Adequate thermal management is often overlooked in LED system design. It is not sufficient to use a header of low thermal impedance. The header itself must be appropriately cooled by attachment to a heat sink, which in turn, must be

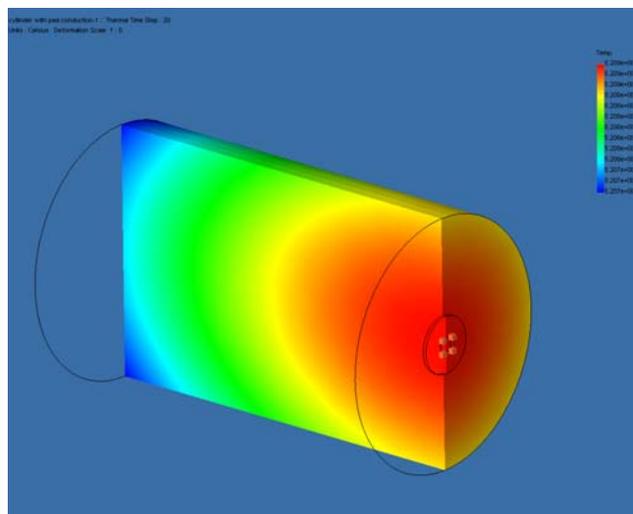


Figure 8. A sectioned view of a heat sink is shown indicating the temperature distribution resulting from the heat load of an LED source.

cooled by conduction, convection or radiation. The best way to optimize material selection and thermal performance is to make use of one of the excellent finite element thermal modeling software packages that are available, many of which interface directly to CAD packages. These thermal modeling packages can take into account material properties, air or liquid flow, and radiation as well as the use scenario, i.e., transient or steady state operation.

Figure 8 shows a typical output of a thermal modeling program for which an LED heat source on the right side of an aluminum cylinder in the form of a small LED array is illustrated. The shading indicates an isothermal gradient. In general it is always good to build a working breadboard of the thermal system to validate the model as a model is only as good as the input it is given and the resolution of the finite elements. Some interfaces are difficult to model such as an interface between two flat metal surfaces that are bolted together, as the thermal impedance will depend on the surface finish, flatness and pressure exerted between the two parts. Resistance to air or water flow and turbulence is also difficult to model, however, software models are continually improving and will be better able to deal with such difficulties as time goes on.

The operating temperature affects LED die lifetime, thus it is critical to understand system-level thermal behavior. There is some debate as to the relative contribution to lifetime degradation due to current density versus temperature, but there is little debate that maintaining sufficiently low junction temperature is critical to achieving long life.

Temperature has other adverse effects on LED performance. Typically, the peak wavelengths of LED die shift toward the red spectrum with increasing junction temperature, which can have serious implications for wavelength sensitive performance requirements. LED wall plug efficiency generally decreases with increasing temperature. This can lead to the need to increase current density to achieve a given output, compounding the lifetime issue due to both increased heat flux and current density. Changes in temperature can also result in stresses on the LED die and wire bonds as well as other system components that could lead to decreased life or catastrophic failure, thus it is important to utilize materials that minimize differential thermal expansion over the operational, storage, and shipping temperature extremes and gradients.

### **2.3.6 Mechanical**

Mechanical design considerations include size, complexity, cost, manufacturability, performance and packaging requirements. One critical mechanical consideration is the type of encapsulant used. Encapsulants can yellow with time, temperature and exposure to short wavelength radiation and can be subject to mechanical failure. The purpose of die encapsulation is two-fold. First, it is generally used as an index-matching medium to increase die extraction efficiency limited by total internal reflection of the light trying to escape from within the die. Secondly, it is often used to mechanically stabilize the wire bonds. Both thermal and UV cured epoxies have been widely used as encapsulation materials. Recently, there has been increased use of silicones as they tend to reduce stresses on wire bonds over greater extremes in temperature, can survive higher temperatures, and generally do not yellow.

## **2.4 An optimized LED package design**

An example of an optimized LED package (patent pending) is shown in Figure 9. An array of closely packed LED die fills the input aperture of a CPC designed for an output half angle of 41.3 degrees. A thermally efficient header design maintains low die temperature and would be mounted to a high performance heat sink, depending on the specific application for which is used. The interface between the back of the header and the heat sink would be filled with a low thermal impedance material such as a silver-filled epoxy, silver-filled grease, solder, aluminum oxide thermal compound, or a high thermal conductivity pad. Leads could be readily attached to the two gold electrodes on the electronics board. A silicone-based encapsulant assures index matching and protects the wire bonds. As mentioned above, the electronics board to which the die are wire bonded could be integrated with the header.

Very recent developments in die fabrication have resulted in true top-emitting die, which are ideally suited for this type of package. Many die geometries, however, emit over their volume, thus some of the light is emitted out of the side of the die. This results in reduced performance for closely packed LED die arrays requiring the die to be positioned about a die width apart to prevent light emitted from one die being reabsorbed by adjacent die. The trend toward true top-

emitting die will allow this type of package to realize its full potential. It is doubtful that any other type of outcoupling device will attain brightness greater than the general CPC geometry shown here, as this package operates very near the theoretical limit of efficiency.

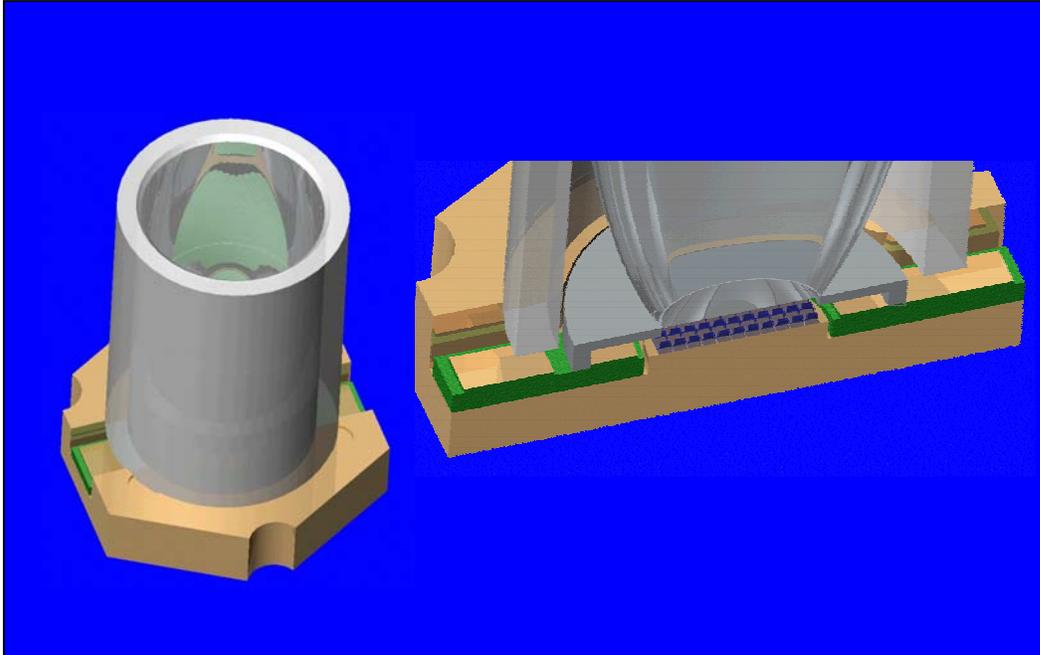


Figure 9. An optimized LED package is shown in rendered view on the left and in cross section on the right (patent pending).

## 2.5 Scanning LED system for increased brightness

The primary limitation for LEDs in achieving brightness levels necessary for demanding applications such as surgical headlights is that LED efficiency and life are closely linked to thermal management and current density. In other words, there are practical limits to the input power that can be applied to an LED. The theory behind the (patent pending) scanning LED technology is that a series of LED light engines can be pulsed at a high electrical input power for a short duration. Each LED light engine can be scanned during its “on” period, and can cool during its “off” period. By efficiently collecting the light from each scanned LED into a common optical fiber, the total brightness can be dramatically increased. This technology will have a competitive advantage even as LEDs become brighter because the scanning technique can be used with any LED, and will provide additional brightness beyond that achievable by static LED packages.

Figure 10 shows a rendered view of one embodiment of a scanning LED system. It uses a multiplicity of LEDs arranged radially about a central scanning mirror. By turning only one LED on at a time in a sequential manner as indicated by the graph in Figure 10, each LED operates at a low duty cycle enabling it to operate at a much increased peak power. This basic technique can be configured in many ways consisting of a minimum of two LEDs to a number only limited by the package constraints. There are, however, diminishing returns on the number of LEDs. The peak output power of each LED does have an upper limit.

Scanning LED technology could be applied to a number of applications requiring brightness and lifetime performance that is unobtainable by conventional methods. These applications include but are not limited to surgical lighting including major and minor surgical lights, headlights and endoscopes, photodynamic therapy, light activated curing, and video projection systems.

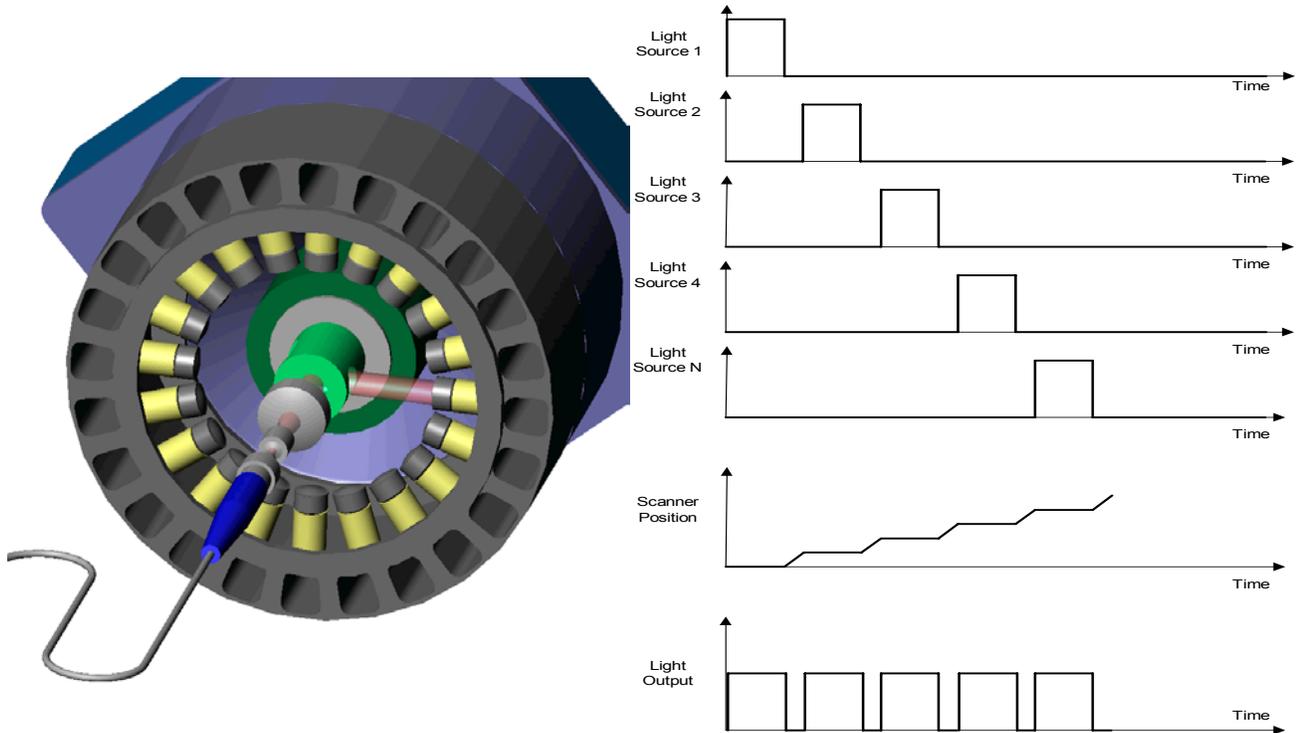


Figure 10. A rendered view of one embodiment of the (patent pending) scanning LED concept is shown on the left. Many LED's can be positioned radially allowing a scanned mirror to direct one LED at a time into the output fiber or aperture. The graph at the right depicts the way in which LED's are scanned sequentially. Each individual LED can be driven at a much higher peak power than a single LED package, thus resulting in significantly higher average output power.

### 3. APPLICATIONS

The optimized LED package presented above and variations there of, have numerous applications across many fields. Sections 3.1 and 3.2 below describe the application of the technology to dental and industrial curing and to major surgical lighting.

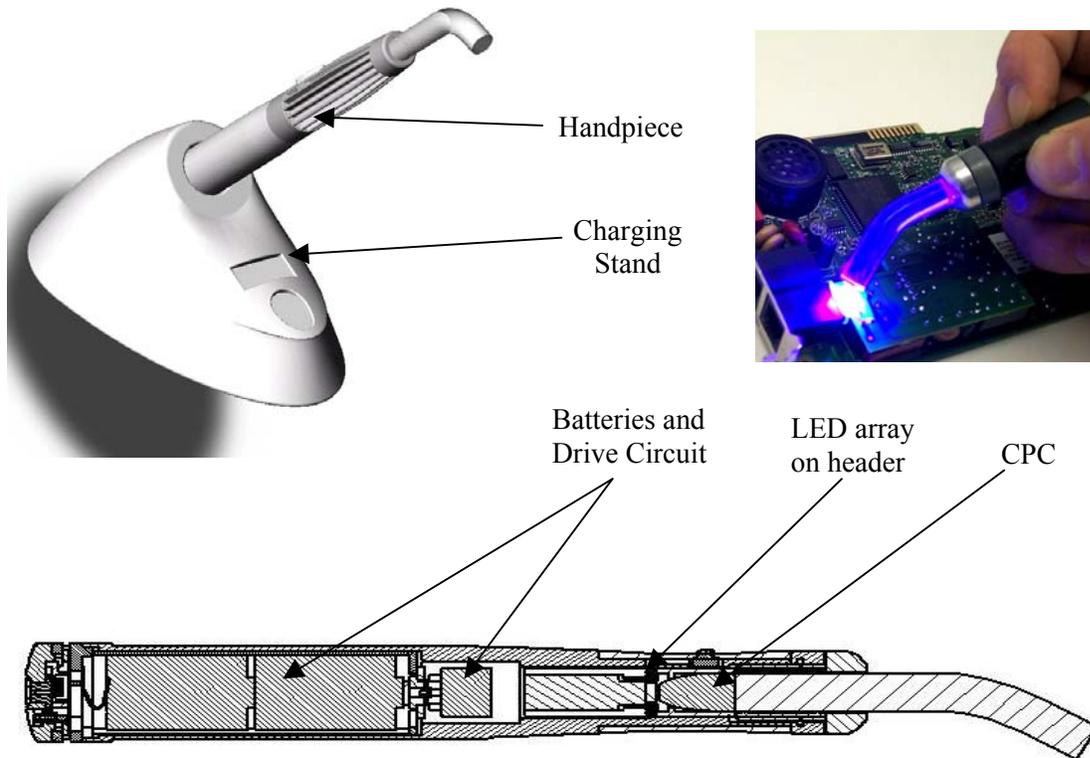


Figure 11. A handheld LED curing system is shown with application to both dental curing and industrial curing of visible light and UV photocurable adhesives (patent pending).

### 3.1 Curing

Figure 11 shows a cross sectional view, a rendered view and an actual picture of a working LED curing pen based on an LED package similar to that described in Section 2.4, above. An LED array substantially fills the input aperture of a CPC. The output aperture is coupled to a light pipe that delivers the LED radiation to the work area. This type of device is well suited to the application of dental curing and also to industrial adhesive curing. The high efficiency of the device results in outputs on the order of  $1200 \text{ mW/cm}^2$  at  $470 \text{ nm}$  out of an  $8 \text{ mm}$  diameter light pipe for dental curing, which rivals the best, and substantially larger, tungsten halogen based systems on the market. The relatively higher efficiency of the shorter wavelength  $405 \text{ nm}$  LED die result in the order of  $3000 \text{ mW/cm}^2$  for hand held industrial curing devices.

### 3.2 Surgical illumination

Figure 12 shows a rendered view of a major surgical light system for patient illumination. The LED light engines relay the emitted light to secondary optics, producing a six-inch pattern at the patient with a photometric intensity greater than  $100,000 \text{ lux}$  and a CRI in excess of 90. The system offers promise to surpass the performance, life and reliability of any other surgical light on the market. It is clear that solid-state lighting has a place in surgical illumination and is likely to supplant other illumination technologies in the near future.

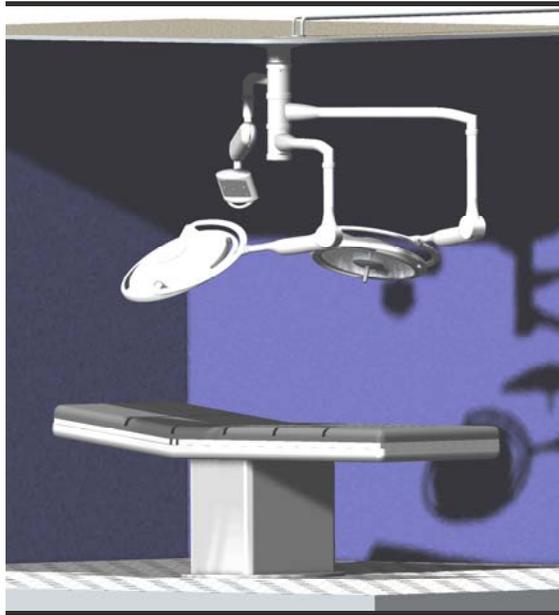


Figure 12. A two head major surgical light is shown for patient illumination. The light engines are comprised of arrays of alternating red and blue die in combination with a yellow phosphor to achieve greater than 100,000 lux within a six-inch diameter pattern with a color temperature on the order of 4300 Kelvin and a color rendering index in excess of 90.

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