Solid-state lighting is a technology of opportunity for a number of niche applications. Such systems do not require imaging optics, which are actually counterproductive. They do need careful light management, however. Enter non-imaging optics.

A light-emitting diode (LED) in its simplest form is a semiconductor p-n junction device. When forward-biased with a direct current (DC), an LED emits photons as a result of the recombination of electrons and holes near the junction. The energy of the photons is determined primarily by the energy bandgap of the semiconductor, where the recombination occurs. III-V compound semiconductors are the materials of choice for LEDs because they have the direct bandgap properties and bandgap energies necessary for efficiently producing visible photons. The best aluminum indium gallium phosphide (AlInGaP) LEDs (red and amber) offer 40% to 50% electrical-to-optical conversion efficiencies. The best indium gallium nitride (InGaN) LEDs (UV, blue, green, and white) achieve 30% to 35% conversion efficiencies.

The drive voltages for AlInGaP LEDs typically range from 1.8 to 3.0 V dc, while drive voltages for InGaN range from 3.4 to 4.0 V dc. In general, LED manufacturers recommend that the junction temperature of all LEDs be kept at less than 125°C to avoid thermal degradation (yellowing) of the encapsulation epoxy. This yellowing greatly reduces light output and lifetime, particularly for blue and green LEDs. The die for ordinary LED packages range from 0.25 to 0.35 mm on a side, while those for the so-called power LED packages (outputs above 1 W) range from 0.90 to 1.10 mm on a side.

LEDs are typically available in three packages: as 5-mm bullet lenses, with typical drive currents of 20 to 40 mA and thermal resistances of 200 to 300°C/W; as surface mount...
devices, with typical drive currents of 10 to 20 mA and thermal resistances of 150 to 300°C/W; and as power LEDs, with typical drive currents from 100 to 350 mA and resistances of 8 to 15°C/W. It is not unusual to find LEDs placed in optically crude reflector cups before encapsulation, such that the overall LED package emits light into angles from ±15° to ±60° for the high power packages.

One of the biggest misconceptions about LEDs is that they are cool light sources. This probably stems from the fact that most people have experience with 5-mm bullet lens packages with typical power consumptions of roughly 0.1 W, perhaps 70% of which is emitted as heat. When dealing with power consumption as low as 0.07 W, one can easily come away with the false impression that LEDs are indeed cool light sources.

Now let us consider a 1500 lm white power-LED replacement for a 100-W incandescent lamp and see if we still believe it. At today’s best efficiency figures of 50 lm/W for a 1 W device, we would require 30 of these LEDs to produce 1500 lm. Assuming that 30% of the power goes into creating light and that 70% goes into creating heat, we would need to dissipate 21 W of heat from a standard Edison lamp socket.

Unlike an incandescent bulb, which emits heat radiatively, LEDs can only get rid of heat through convection and conduction, making active cooling almost inescapable. Indeed, the ability of incandescent lamps to get rid of excess heat via radiative transfer is their fundamental advantage over LEDs.

Non-Imaging Optics

LEDs enjoy a pair of fundamental advantages over incandescent lamps, fluorescent lamps, and high-intensity discharge sources: They are intrinsically small and do not require a large glass envelope, as do many of their competitive light sources. As a consequence, LED emission can be easily directed into specific lighting patterns or fields of view, requiring from one half to one third the lumens needed by competing light sources like fluorescent bulbs, which are less easily controlled and directed.

We can broadly classify optics as imaging or non-imaging (see figure 1). The field of imaging optics has been around for more than 300 years and is the optics of parabolas, ellipses, thick lenses, thin lenses, and Fresnel lenses. The one characteristic that all of these optical technologies have in common is that they form images of objects. As the lighting industry developed during the past 200 years, it was natural to incorporate this already existing imaging technology into new lighting systems.

A little thought experiment will show that imaging optics provide far from an optimum solution, however. Consider a parabolic mirror used to project a beam from an automobile headlamp. Depending on the depth of the parabola, only about 40% of the light leaving the bulb will reflect off the parabolic mirror to be collimated and projected as a beam. The other 60% leaves the headlamp in an unguided way. At best, unguided light is not useful; at worst, as in automotive forward lighting, it is a negative in the form of glare.

The ideal optical system should completely surround the source, gathering up every emitted photon and delivering them into a prescribed field of view or flux pattern, regardless of whether an image is formed or not. This is exactly what the field of non-imaging optics seeks to do.

An imaging optical system maintains a strict juxtaposition of source points A and B, such that an exact image of the source is formed at the receiver (for example, your eye, photographic film etc.). Notice in figure 1 that a non-imaging system relaxes the requirement for image formation and instead requires only that all the flux leaving the source gets redirected to the receiver, regardless of any mixing of the light rays that may occur during the process. As an analogy, imagine that you just completed a complex jigsaw puzzle that now needs to be transported from point A to point B. Imaging optics would require that the transport be completed without rearranging any of the pieces, while non-imaging

![Figure 1](image1.png) Non-imaging optics focuses on the optimum transfer of luminous power rather than on forming an image. This eases the constraints on the design.

![Figure 2](image2.png) In the method of strings, we imagine a string (blue) running along ABC such that it intersects rod CE (red) at the perpendicular. If we fasten the string to the rod by a slip ring and maintain perpendicularity while holding the string taut, the angle in the strings traces out curve BD (green)—the concentrator wall.
known as the edge-ray method or the method of strings. Consider a flat LED emitter situated at the entrance aperture AB and emitting its light into ±90°. Assume this light is collimated into ±Θ at the exit aperture CD (see figure 2). According to the edge-ray method, we should construct a reflector that will take the most extreme rays, leaving the LED die—in this case, the ray along AB and the ray along AD—and redirecting them to exit our non-imaging device at point C and point D, inclined at angle Θ at the exit aperture CD; if we can control these extreme rays, then all other rays will lie within the region bounded by them, leaving the LED.

Consider a rod CE inclined at an angle Θ to exit aperture CD. Now imagine a piece of string attached via a slip ring and positioned at point C on the rod, such that the string is taut and stretched from point CBA. Now, assuming a constant string length, allow the slip ring to move along rod CE such that the string (ray) is parallel to the preceding ray in every successive position until the concentrator wall BD has been traced out. This construction gives the concentrator (or more aptly, in this case, the collimator wall) profile for the non-imaging device. This method can be extended to dielectric optical devices and to more sophisticated objects, but article space does not allow for these excursions here.

Non-imaging lenses can be more sophisticated, as with a total internal reflection (TIR) lens that can capture almost 100% of the light leaving the LED light source and yet has an f/# of less than 0.25—several times smaller than that of a typical imaging lens. TIR lenses can be designed to direct LED emissions sideways (right).

optics allows for the complete mixing of the pieces, requiring only that the total number of pieces remain the same throughout the process. One can imagine that this non-imaging transport could be done more efficiently, compactly, and perhaps more easily than imaging transport.

Designing the Lens
The field of non-imaging optics got its start in the United States in the 1930s in luminary design at lighting companies such as General Electric. The field did not really begin to take hold, however, until the 1970s when Roland Winston, then at the Physics Department of the University of Chicago (Chicago, IL), and Walter Welford of the Physics Department of University of London (London, UK), began formulating the principles, theory, and mathematics of non-imaging optics. One of its first applications was in the field of solar energy concentration for both photovoltaic and solar thermal systems. Subsequently, applications such as fiberoptic coupling, LCD backlighting, IR countermeasures for heat-seeking missiles, and sensors for high-energy particle physics all came to benefit from the increased optical efficiency and compactness supplied by non-imaging optics. In fact, it is not unusual for non-imaging optics to offer optical efficiency increases of 50% to 150% over corresponding imaging optical systems while remaining typically four to twelve times more compact.

A number of methods exist for designing non-imaging optical systems. The simplest and most intuitive of these is known as the edge-ray method or the method of strings. Consider a flat LED emitter situated at the entrance aperture AB and emitting its light into ±90°. Assume this light is collimated into ±Θ at the exit aperture CD (see figure 2). According to the edge-ray method, we should construct a reflector that will take the most extreme rays, leaving the LED die—in this case, the ray along AB and the ray along AD—and redirecting them to exit our non-imaging device at point C and point D, inclined at angle Θ at the exit aperture CD; if we can control these extreme rays, then all other rays will lie within the region bounded by them, leaving the LED.

Consider a rod CE inclined at an angle Θ to exit aperture CD. Now imagine a piece of string attached via a slip ring and positioned at point C on the rod, such that the string is taut and stretched from point CBA. Now, assuming a constant string length, allow the slip ring to move along rod CE such that the string (ray) is parallel to the preceding ray in every successive position until the concentrator wall BD has been traced out. This construction gives the concentrator (or more aptly, in this case, the collimator wall) profile for the non-imaging device. This method can be extended to dielectric optical devices and to more sophisticated objects, but article space does not allow for these excursions here.

Non-imaging lenses can be more sophisticated, as with a total internal reflection (TIR) lens that can capture almost 100% of the light leaving the LED light source and yet has an f/# of less than 0.25 (see figure 3). Recall that we define f/# as the ratio of the focal length to the lens aperture. Imaging lenses typically feature f/#s in the range of one to five, which implies that they are four to 20 times larger than TIR lenses. TIR lenses can be designed to redirect almost all of the light leaving the LED die to the side, a very desirable property for injecting light from an LED into a thin plastic waveguide with nearly 100% efficiency.

With proper non-imaging optics, solid-state sources can provide effective solutions for a range of niche applications. As the lighting community better understands non-imaging optics, LEDs will broaden their market penetration.

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References

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