

# Diode laser-excited phosphor-converted light sources: a review

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**Abstract.** Solid-state lighting has been moving into new directions since its emergence in the 1990s. Light-emitting diodes (LEDs) and LED-based luminaires have seen impressive developments over time and now much research interest is being devoted to the development of a closely aligned lighting technology, based on using laser diodes. In many ways, this is similar to LED-based lighting, but in many ways it is also very different because of the peculiarities of semiconductor lasers and of laser-emitted light. This broad overview looks at recent and on-going developments in the field of diode laser-based lighting technologies. In doing this, it examines the role of laser diodes, phosphors, and system design in enabling the creation of illumination systems that are fit for various application requirements. Phosphors suitable for pumping with laser diodes have been given emphasis. Sufficient tutorial context is also provided so that readers can easily appreciate the import of various developments. Finally, the review also briefly looks at anticipated future developments in this field. © 2022 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.OE.61.6.060901](https://doi.org/10.1117/1.OE.61.6.060901)]

**Keywords:** solid-state lighting; laser diodes; phosphors; color conversion.

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## 1 Introduction

Over the past two decades, solid-state light sources that rely on a semiconductor light-emitting device to generate light for illumination purposes have largely taken over from incandescent and discharge lamps.<sup>1-4</sup> These new light sources have the benefits of small size, high efficiency operation, long operating lifetimes, and environmental sustainability. Given that space lighting accounts for a substantial portion of humankind's total energy usage, this shift has been a defining development of our times. In the United States alone, around 219 billion kWh of energy is used annually for artificial lighting. Had highly energy efficient solid-state lighting not been invented, a much larger amount of energy would have been used for this purpose.

Light-emitting diodes (LEDs), which first ushered in the era of solid-state lighting beginning in the late 1990s, have proliferated to the extent of becoming ubiquitous. From domestic lighting to architectural illumination and from lighting up our roads and fields to entire factory floors, LED-based luminaires are now to be found everywhere. During the past couple of decades, LED technology has matured, and these devices and systems based on them are now commodity items—manufactured in very large numbers and sold with a relatively small profit margin. The march of technology, however, never stops. A similar but different class of lighting systems, based on the use of semiconductor laser diodes (LDs) instead of LEDs, has garnered attention from technologists and system developers since around 2010.<sup>5,6</sup> Over the course of a decade, lighting systems employing LDs as sources for pumping phosphors have been developing rapidly and finding favor in a number of application areas where their distinct capabilities set them apart from LED-based systems.<sup>7,8</sup> At the time of this writing, LD-based phosphor-converted lighting systems are available for certain specific applications where these light sources are much better suited than their LED-based counterparts. Such applications require either a light source of exceptionally high brilliance or high directionality, or both. With the passage of time, however,

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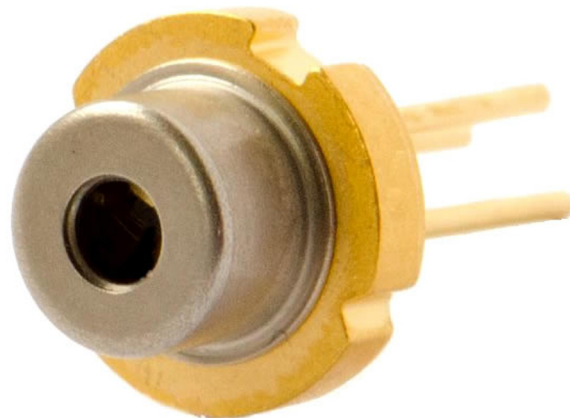
it is likely that LD-based luminaires will also see service in more traditional settings, such as illumination sources for homes and offices. This review looks at LD-pumped light sources from the perspectives of system design and wavelength conversion. In doing so, it strives to present an informative account of what has been achieved so far, and at the same time also provides a tutorial context to the various topics under discussion.

In what follows, we first look at the broad outlines of LD-powered phosphor-converted light sources from an optical system design perspective. Next, as the topic of emphasis, various kinds of phosphors that are currently being used in LD-powered luminaires are examined. Finally, we take a brief look at some of the application areas and future prospects for LD-based lighting systems.

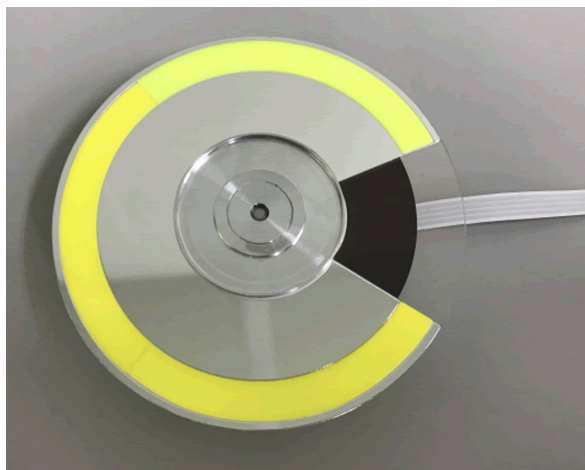
## 2 Optical System Design for LD-Based Solid-State Lighting

The availability of moderate and high-power blue-emitting laser diodes at a reasonable price has been one of the driving forces behind the development of diode-pumped light sources. Semiconductor laser diodes emit radiation in the same range of wavelengths as is emitted by LEDs that are used for making LED-pumped light sources. Thus, it is just the type of pump source that changes from LEDs to LDs. Although the peak pump wavelengths remain more-or-less the same, LEDs and LDs are very different—not only in their structures, but also in the characteristics of light that they emit. Light emitted by LDs is highly monochromatic, very intense, directional (collimated) and exhibits a high degree of coherence. These attributes impose unique design requirements on LD-powered luminaires. At the same time, the peculiar characteristics of LD light, mentioned above, also open the doors for new application areas that particularly suit LD-pumped light sources.<sup>9</sup>

Almost all LDs (see Fig. 1) for these applications are made from the gallium nitride (GaN) and indium gallium nitride (InGaN) material system. GaN/InGaN LDs employ a quantum well structure, grown through metal oxide chemical vapor deposition (MOCVD) technology where the well regions are formed of InGaN ternary alloy semiconductor, and the barrier regions are composed of GaN layers. This scheme has been perfected over the past many years—initially for violet-emitting (~405 nm) LDs but later also for blue-emitting (~450 nm) LDs. In more recent years, this technology has also been extended to make green-emitting lasers that are increasingly replacing diode-pumped solid-state lasers based on non-linear wavelength conversion crystals. LEDs suffer from the so-called droop effect when operated at increasingly high drive currents. Their operating efficiency begins to fall beyond a certain value of forward current. This effect has been attributed to a number of different phenomena, such as carrier escape and Auger recombination, but no solution to avoid it exists. LDs, on the other hand, do not suffer from droop. Thus, LDs are clearly superior to LEDs where one needs to pump luminescent wavelength converters with very high photon flux to generate intense light beams. Wierrer, Jr., has compared



**Fig. 1** A typical low to medium power LD in a metal can package.



**Fig. 2** A phosphor wheel for use in LD-pumped white light sources.

LDs and LEDs from this perspective and has demonstrated the superiority of the former compared to the latter.<sup>10–12</sup>

An LD-pumped solid-state lighting system necessarily differs, substantially, from any LED-pumped counterpart because of the very different characteristics of LD light, when compared with LED light. The intense and directional nature of LD-emitted radiation requires a very different design for LD-based lighting systems. Whereas simply placing a coating of a suitable phosphor, mixed with a binder, on top of a pump LED is sufficient to make a phosphor-converted LED light source, this simple architecture cannot be used where pumping is performed by LDs. Remote phosphor arrangements, where the phosphor is spatially separate from the pump source, are employed.<sup>13,14</sup> Furthermore, the phosphor has to be used in such a way that it is not damaged from the intense LD pump radiation. This may require the use of negative focal length (concave) lenses to expand the beam before striking the phosphor or use is made of a spinning phosphor-coated plate, as shown in Fig. 2. Here, the incident laser spot illuminates all around the periphery of the wheel as it spins, distributing the thermal load and photon flux uniformly over a much larger area than is the case with static phosphor pumping. Currently, most sources designed for very high output white light flux, such as those used for cine projection, makes use of spinning phosphor wheels.

Static phosphor pumping with expanded LD beams is used for lower power lighting systems. George et al. have described such an LD-based lamp system in detail.<sup>15</sup> Their design resembled a traditional lamp (see Fig. 3), with a laser diode module in the base, followed by a beam expansion lens and finally a phosphor-coated plate. They reported good Commission Internationale de l'Eclairage color coordinates and good spectral characteristics of output light. In other cases, where a more directional light output is desired, the converted radiation often requires a separate optical arrangement to either collimate it or otherwise form a desired beam pattern. Thus, LD-pumped luminaires are usually substantially more complex in their design than their LED-pumped counterparts. This is one reason for their higher cost, besides the higher cost of the pump source itself. A simpler design that uses a light diffusing phosphor plate has been described by Chi et al.<sup>16</sup> Their implementation allowed them to not only serve as a source of illumination but also to allow pulsed blue LD light to perform a data communication function. This combination is desirable in certain applications and is one where LD-pumped sources can easily displace LED-based luminaires. Other transmissive LD-pumped phosphor-converted light sources have been described by Wu et al.<sup>17</sup> and by Sun et al.<sup>18</sup>

The optical pathway design for LD-based luminaires can be easily carried out by the use of various optical simulation software tools. LightTools and TracePro are two of the several software packages that are available to system designers for this purpose. Desired optical component configurations and light ray pathways can be set up in such tools and used to create a detailed ray trace pattern to show the predicted path that the light will take through the system. These simulation tools also allow estimates of stray light, input and output fluxes, and overall radiant

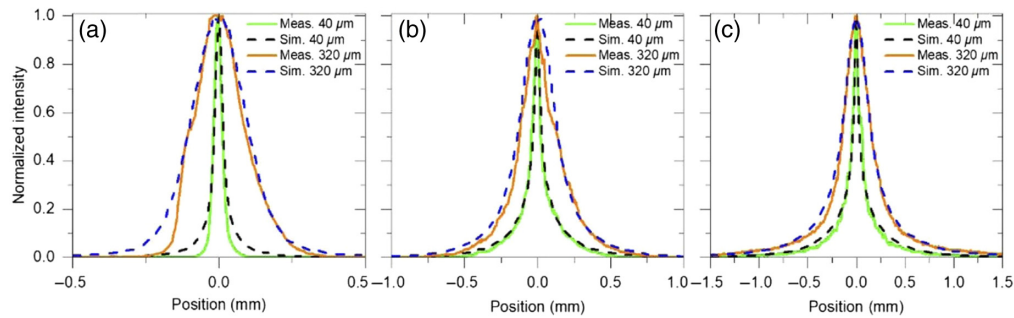


**Fig. 3** A lamp style LD-pumped phosphor-converted white light source.

throughput to be obtained. Changes can be made to component placements and their volumetric and surface properties to explore how such changes will affect the flow of light in systems being designed. Such modeling is very useful during the initial stages of lighting system design, and also when desired modifications have to be made to a system at a later design stage.

Most high-powered LD-pumped lighting systems employ single crystal yttrium aluminum garnet (YAG) ceramic or alumina-YAG composite phosphors, as is described later in this paper. Unlike lamp-like luminaires, such systems excite the phosphor directly, without on-purpose diverging the laser beam with any optical element. The LD beam is then incident on the phosphor surface and the wavelength up-converted light is emitted in either a transmissive (pass-through) or reflective geometry. The latter is more common as the incident light gets to make two passes through the phosphor material and thus optimum wavelength conversion could be achieved. Because no lenses are used (except for any laser beam shaping lens), the converted light retains much of the directionality of the incident laser pump beam. This makes this arrangement very useful for applications where low-divergence light beams are one of the key requirements. This geometry also helps with reducing thermal quenching because the phosphor crystal can be mounted on a mirror-like metal surface that also acts as a heat sink and can effectively remove heat from the phosphor crystal. Krasnoshchoka et al. have studied the size of the luminescent spot on the phosphor, as a function of the size of the incident blue LD pump beam.<sup>19</sup> They found that the surface roughness of the phosphor crystal has a very strong effect on the size of the converted beam spot. Increased roughness led to increase in the size of the luminescent spot. This can be seen in Fig. 4 where the spread of the luminous spot for two different incident laser pump spots sizes (40 and 320  $\mu\text{m}$ ) can be seen on, (a) the transparent ceramic Ce:YAG, (b) composite ceramic Ce:YAG, and (c) Cryphosphor. For the two latter cases, there is considerable spread of the converted luminous spot on the surface of the crystal phosphors. All plots have been normalized in this illustration for ease of spread comparison. Cryphosphor—mentioned later, is a commercial single-crystal phosphor with a roughened surface. The dashed lines in the plot are simulations of beam spot spread for each case. The spread of the converted spot, relative to the pump spot, degrades the luminous exitance of any laser-pumped single-crystal phosphor converter-based light source. A reflective backing to the phosphor crystal also increased the luminescent spot size by increasing the chances of scattering through the phosphor volume as the incident light makes its way through the wavelength conversion medium. These observations are of importance for those optical systems where narrow converted beams are desired.

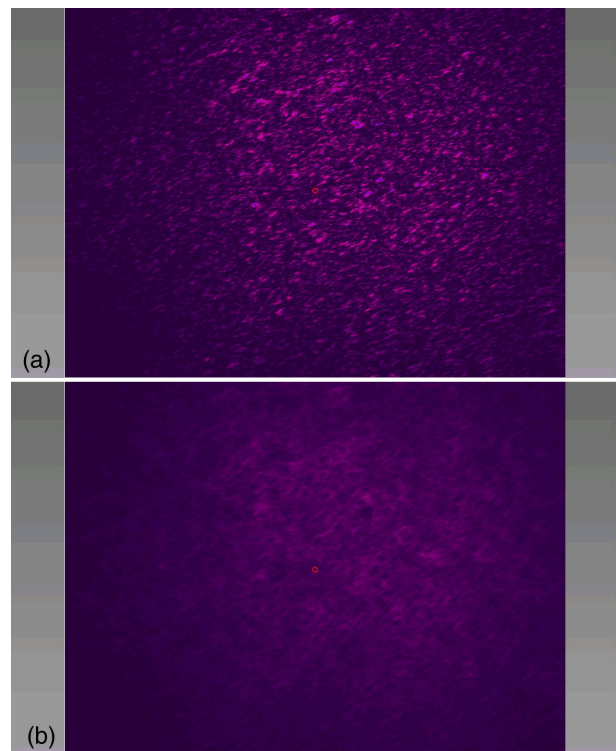
The quality of light available from LD-pumped systems can be improved through approaches similar to those that have been taken with LED-pumped light sources. Thus, the amount of red light component can be increased by either by mixing a red-emitting phosphor with the main phosphor or by adding a supplemental red LED or LD to provide additional red light. The latter



**Fig. 4** Measured (solid lines) and simulated (dashed lines) luminescent spot profiles at 40 and 320  $\mu\text{m}$  incident blue laser spot sizes for (a) transparent ceramic Ce:YAG, (b) composite ceramic Ce:YAG, and (c) Cryphosphor. Note the different x-axes scales. Reprinted with permission from Ref. 17, © The Optical Society.

technique has been described by Wu and colleagues from the Chinese Academy of Sciences.<sup>17</sup> A different design has been described by Dubey et al. that employs a cylindrical surface-ground acrylic rod, coated with a cerium-doped YAG phosphor (YAG:Ce).<sup>20</sup> LD light is coupled into the rod that scatters the light inside its volume. Blue LD light striking the curved surface of the rod from the inside is converted to broadband white light. The arrangement is compact and looks like a 30 cm long fluorescent tube light. This arrangement allows a number of design parameters, such as rod length, rod diameter, and rod's internal structure to be altered in order to achieve optimum illumination characteristics. Yet another design, verified both through ray tracing and actual fabrication, relies on a cone-shaped lens surrounded by phosphor material. LD light passing through the cone lens is appropriately directed inside the surrounding phosphor volume in such a manner that heating effects are minimized and the phosphor's conversion efficiency is maintained at even very high LD fluence levels.<sup>21,22</sup>

Whether a traditional lamp-like or a collimated beam LD-pumped phosphor-converted light source is built, both have to contend with the coherence inherent in the pump light. Light from



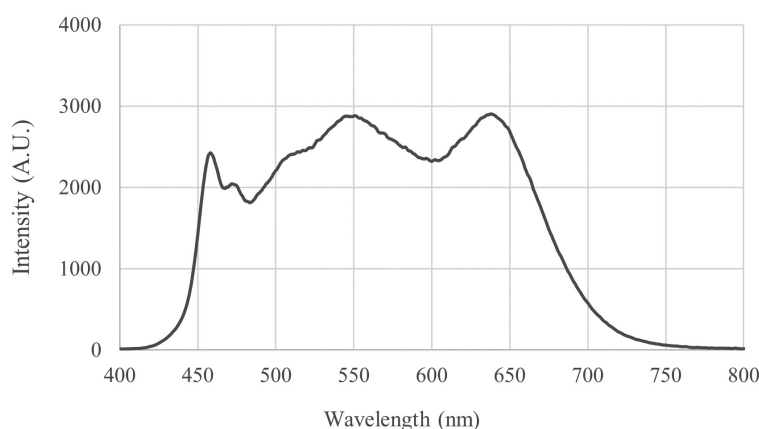
**Fig. 5** Speckle from laser pump light (a) and from the down-converted light (b).

LDs has a lower spatial and temporal coherence than more traditional gas lasers, but its coherence is more than enough to cause wave interference artifacts in light, both before and after it has interacted with a phosphor. For phosphor-less, direct laser beam illumination systems (such as those sometimes used for cine projection), coherence can give rise to troublesome speckling. On surfaces illuminated with pure un-converted laser light, speckle appears both unsightly and results in the reduction of visual acuity, i.e., loss of perceptible resolution. Aquino et al. have investigated the amount of speckle present in LD-pumped phosphor-converted light sources.<sup>23</sup> Their findings indicate that scattering from phosphor particles in a pass-through (transmissive) geometry tends to very effectively de-phase coherent radiation so that converted radiation coming from the phosphor has greatly reduced coherence. Thus, light from LD-pumped phosphor-converted sources exhibits very little speckle, which is hardly noticeable, as can be seen in Fig. 5. Figure 5(a) shows speckle from a pump laser beam whereas Fig. 5(b) shows speckle visible in the down-converted light. The reduction of contrast and the elimination of “hot spots” show that the speckle is greatly reduced. Commercial laser-phosphor lamps used in automobiles and projectors exhibit minimal speckle due to this reason, and this has helped in their rapid adoption in vehicles and cine projectors.

### 3 Phosphors for Solid-State Lighting with LD Excitation

Luminescent materials, usually called phosphors in this context, are central to the operation of all solid-state light sources that rely on changing the wavelength of a pump source to a desired spectral distribution. Phosphors do this by absorbing radiation (getting pumped or getting excited) from a pump source, which can be either an LED or an LD, and emitting radiation in a longer wavelength band. The vast majority of phosphors perform energy down-conversion i.e., absorb more energetic photons at shorter wavelengths, as the pump radiation, and then emit less energetic photons at longer wavelengths. The difference in wavelength between the absorption and emission spectral peaks represents the energy that is lost in the conversion process. It is called the Stoke’s shift. The lost radiant energy appears as heat in the phosphor material. While phosphor-based LEDs have now been in existence for many years (all LED bulbs, for instance are based on them), the more recent advent of LD-pumped phosphor-converted light sources has made it clear that LD-pumpable phosphors often need to satisfy a different set of requirements when compared with phosphors that are pumped with LEDs.<sup>24</sup> This is discussed in more detail below, but in brief, LD phosphors should have a higher damage threshold to face the intense radiation from LDs, and also should have radiation absorption characteristics that match the narrow emission wavelengths from typical LDs.

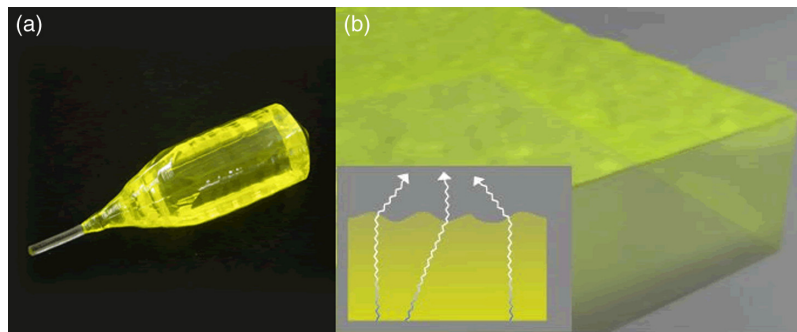
Luminescent wavelength-conversion materials (phosphors) are central to any solid-state lighting technology.<sup>25</sup> Prior to the development of phosphor-based luminescent conversion LEDs, phosphors were heavily used for many other applications, such as cathode ray tubes and plasma display panels.<sup>26</sup> Thus, phosphor technology was already fairly mature when LEDs came to the scene. Both LED- and LD-pumped white sources make use of phosphors to generate a wide spectral output that can be used for illumination purposes. For space and object lighting applications, a wide spectral coverage is desirable and, thus, use is made of broadband phosphors that emit light in a wavelength band that covers 100 nm or more of the visible spectrum. For projection and other image display applications, on the other hand, it may be desirable to have wavelength conversion to narrowband emissions. Suitable phosphors exist for both application domains, with a preponderance of wideband phosphors over narrowband ones. Cerium-doped YAG (YAG:Ce) is a prime example of a wideband illumination-quality phosphor that has been long used for solid-state lighting applications.<sup>27–33</sup> When pumped by a blue-emitting pump source in the 430 to 470 nm region, YAG:Ce emits over a wide wavelength band that appears yellow to human eyes. With appropriate phosphor coating thickness, it is possible to “bleed off” some of the pump radiation, which, in combination with the phosphor emission, makes the resulting mixed light appear white to our eyes. YAG:Ce is also widely used in LD-based white light sources because of its good performance, robustness, inertness, high thermal conductivity, and wide spectral coverage. Broadband phosphors also exist for single-color light generation. CaS:Eu, for instance, can generate a broad red spectrum, whereas certain lutetium-containing



**Fig. 6** Spectrum of light wavelength-down-converted by a proprietary broadband phosphor composition.

phosphors can generate a broad green spectrum when pumped with a blue-emitting LED or LD. A truly broadband white light source can be created by combining individual broadband red, green, and blue LED- or LD-driven sources or by compounding a suitable phosphor mixture with broadband phosphors that can be pumped by a single pump source to accomplish a very wide spectral coverage, as can be seen here in Fig. 6, which shows an almost complete visible spectrum-filling light source created with a blue LED and a phosphor mixture.<sup>34–36</sup> The mixed phosphor approach is the preferred one because it does not involve the use of light mixing optics to create a homogenous spectral output. Light mixing optical arrangements are both expensive and suffer from operational inefficiencies so that this approach is only taken if active tailoring of spectrum by electronically controlling the separate color emitters is of prime importance. Where compounded phosphor mixtures are used, care has to be taken to avoid re-absorption of light and to ensure that all phosphor components exhibit strong absorption of light at the pump wavelength. When it comes to laser-pumped phosphors, their light absorption characteristics can assume special significance. This is because LDs have very narrow emission widths, compared to LEDs. The narrow emission line might easily miss the spectral regions where certain phosphors have strong radiation absorption. This is much less of a problem with LED pump sources because they have relatively broad spectral emissions that can overlap well with a phosphor's absorption regions. Furthermore, with LDs as pump sources, the aerial power density (in  $\text{W}/\text{cm}^2$  or  $\text{mW}/\text{cm}^2$ ) can be very high and, thus, phosphors have to be capable of handling high radiant power levels without getting damaged.

LED pumping usually makes use of phosphors that are mixed with an organic binder resin, such as polycarbonate or silicone. This is made up as a slurry, which is dispensed and coated directly on top of bare LED chips. Less prevalent are remote phosphor arrangements where the phosphor is not in direct physical contact with the pump LED. This latter arrangement is used with all LD-pumped luminaires. However, even without physical contact between the LD and the phosphor, and thus any heat transfer from an operating LD to the phosphor, the intense light from the laser beam can cause substantial increase in phosphor temperature, as well as cause saturation due to high photon flux. For these reasons, organic binders are, generally, not used with phosphors that are pumped with LDs. A recent study from Lithuania has reported on the addition of hexagonal boron nitride particles in phosphor + silicone compositions to raise the thermal conductivity, and the temperature capability, of organic resin-based phosphor coatings.<sup>37</sup> However, due to increased light scattering, this does not appear to be an optimal solution where very high power, focused laser beams are used for phosphor pumping. An alternative has been the use of phosphor-in-glass (PiG) composites where phosphors are embedded in a glass matrix.<sup>38–43</sup> This luminescent material is prepared by mixing phosphor powders with finely divided glass powder and sintering the mixture to prepare a uniform solid body that is polished to obtain a phosphor plate. Glass confers highly increased temperature resistance, compared to organic binders. PiG materials have been used in both high-power LED- and LD-based luminaires. However, at high LD power levels, glass-based phosphors also prove inadequate, and an even better alternative is



**Fig. 7** A cerium-doped YAG crystal boule, grown by the Czochralski process (a). Section of a phosphor plate cut from a boule (b). The top surface is etched to improve light extraction efficiency.



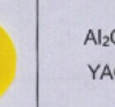
needed. Single-crystal phosphors have been developed for this purpose. These consist of a one-piece monocrystalline phosphor that can be held in various ways and requires no glue or binder.<sup>44–46</sup> Cerium-doped glass-ceramic phosphors, based on YAG host were investigated first,<sup>47</sup> followed by monolithic cerium-doped YAG phosphors. Extensive studies of temperature-dependent reduction of yellow luminescence from YAG:Ce phosphors were carried out by Bachmann et al. during 2008 and 2009,<sup>48</sup> which showed that single-crystal phosphors were superior to powder phosphors, especially for LD-pumped applications. Similar conclusions were also reported by a team from Brunel University in the United Kingdom.<sup>49</sup> Several companies, such as Crytur of the Czech Republic, now produce single-crystal YAG:Ce phosphor. This material is grown by the Czochralski technique (see Fig. 7). Cryphosphor™ manufactured by Crytur, for example, shows 94% internal quantum efficiency and is capable of working at up to 300°C. This is a significant improvement over earlier YAG:Ce phosphors that had an upper operating temperature limit of 250°C.<sup>50</sup>

Various cerium-doped garnet single-crystal phosphors have been investigated with LD pumping by Balci et al.<sup>51</sup>  $\text{Ce}^{3+}$  ions present in these phosphors generate efficient conversion from blue LD light to wide band visible light due to 5d to 4f electron transitions. Addition of gadolinium (Gd) to single-crystal YAG:Ce phosphor creates a red shift to longer wavelength emission, whereas the addition of Lu produces a blue shift to shorter wavelengths. These elements partially or completely replace Y in the YAG host and lead to intrinsic charge deformation and orbital hybridization, which results in spectral peak shifts.<sup>52</sup> Thus, the addition of one of these elements can be used to appropriately tailor the emission band and emission peak to desired values. They also found that LuAG:Ce is highly thermal resilient and can withstand very high temperatures before quantum efficiency degradation sets in. The same conclusion was also reached in another study on this phosphor that was reported by Kang et al.,<sup>53</sup> as well as in research reported by Zhang et al.<sup>54</sup> This phosphor can be used at LD optical power densities as high as 1 kW/cm<sup>2</sup>. Liu et al. have also reported red shift produced by the addition of Gd to single-crystal YAG:Ce phosphor.<sup>55</sup>

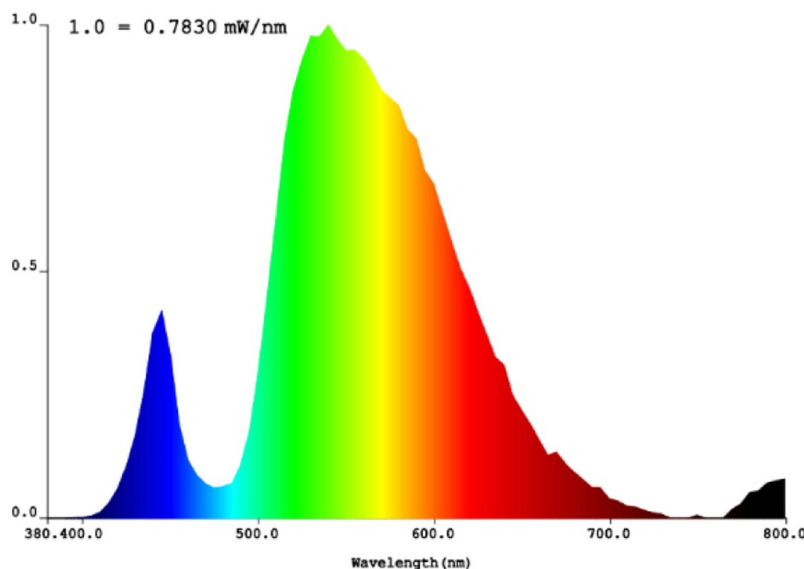
Single-crystal phosphors have been developed beyond YAG:Ce by adding additional material to the YAG melt during Czochralski crystal growth. Such phosphors are called composite phosphors. Most commonly, the additive material is alumina ( $\text{Al}_2\text{O}_3$ ).  $\text{Al}_2\text{O}_3/\text{YAG}:\text{Ce}$  composite phosphors, thus, formed have remarkable properties that have made them extremely attractive for LD-pumped illumination applications.<sup>56,57</sup> Figure 8 shows a set of phosphor plates containing different relative amounts of YAG and alumina. As can be seen, increasing the amount of the latter reduces the transparency of the phosphor by increasing bulk scattering. These wavelength up-converters were first used for automobile headlights—an application that is extremely well-suited for LD-based light sources. A typical spectrum obtained with 450 nm blue light excitation of a YAG-alumina composite phosphor plate from a laser diode is shown in Fig. 9, which shows broadband conversion centered at 540 nm.

The Korean team of Song et al. have described the design of laser-driven phosphor-converted luminaires for automotive applications using composite  $\text{Al}_2\text{O}_3/\text{YAG}:\text{Ce}$  single-crystal phosphor.<sup>58–60</sup> Often called a ceramic phosphor plate, this single-crystal phosphor exhibits two remarkable advantages over simpler single-crystal YAG:Ce phosphor. First, it has higher



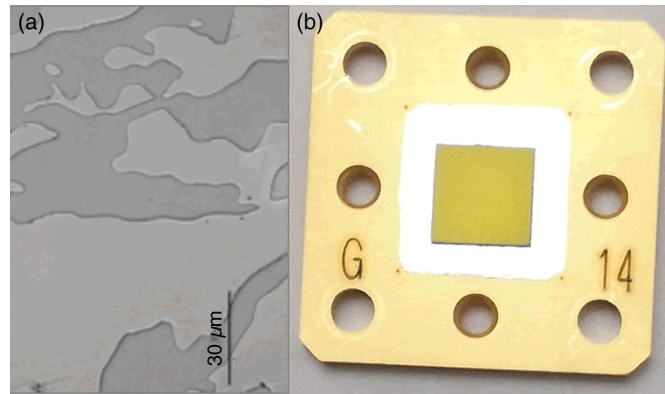
Sample number	1	2	3	4	5	6
YAG (wt%)	36%	40%	45%	50%	60%	70%
Sample photos						
Sample number	7	8	9	10	11	12
YAG (wt%)	80%	90%	95%	99%	99.90%	100%
Sample photos						

**Fig. 8** Photographs of Ce-doped  $\text{Al}_2\text{O}_3$ -YAG ceramics with different relative amounts of YAG and alumina. Reprinted with permission from Ref. 54, © The Optical Society.



**Fig. 9** Excitation and wavelength up-conversion spectrum from a composite YAG-Alumina phosphor plate. Reprinted with permission from Ref. 54, © The Optical Society.

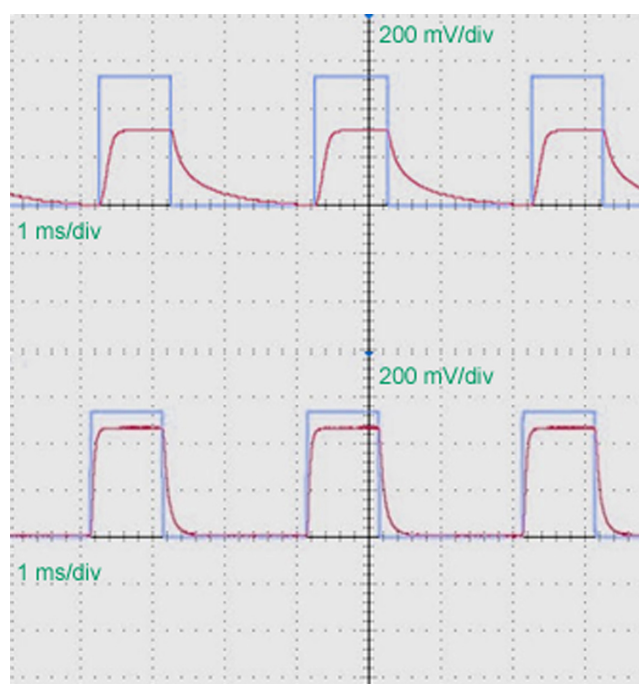
temperature endurance because of the high thermal conductivity ( $\sim 18.5 \text{ Wm}^{-1} \text{ K}^{-1}$ ) of alumina inclusions. This increases both the luminance quenching temperature and the optical damage threshold, enabling it to be used with significantly higher incident laser beam intensities. The second advantage comes from the random alumina phase inclusion within the YAG matrix. With the proper amount of alumina admixture, random continuous and quasi-continuous alumina regions get formed within the YAG host, as is seen in Fig. 10(a). These regions act as conduits for light to pass through, which gives a waveguide-like effect. This enables light to be properly extracted from the confines of the phosphor and, thereby, enhances the external quantum efficiency of the composite single-crystal phosphor. Both advantages confer great operational benefits to LD-based lighting systems, and this has resulted in such composite phosphors becoming established as the conversion medium of choice for high fluence wavelength up-conversion in LD-pumped luminaires. Phosphor crystal attached to an anodized aluminum heat sink is seen in Fig. 10(b).



**Fig. 10** Alumina regions interspersed within a YAG matrix of a composite phosphor crystal (a). A YAG:Ce/Al<sub>2</sub>O<sub>3</sub> single-crystal phosphor plate mounted on a 1 cm × 1 cm aluminum heat sink (b).

Further improvements in this direction are expected from better thermal engineering of the phosphor carrying substrate, e.g., use of high purity silver or diamond-like carbon films as the immediate surface to which the phosphor crystal is bonded. A research group from the Chinese Academy of Sciences has also studied composite cerium-containing alumina-YAG phosphors.<sup>61</sup> Their results show that the inclusion of an optimized amount of  $\alpha$ -Al<sub>2</sub>O<sub>3</sub> particles, of selected sizes, enables simultaneous optimization of light propagation, luminous efficiency, and thermal stability of luminescence, for high power phosphor-converted lighting systems energized by LDs. Cozzan et al. have also described composite Al<sub>2</sub>O<sub>3</sub>/YAG:Ce single-crystal phosphors but made using a spark plasma sintering technique.<sup>62</sup> Their studies reveal similar performance metrics for this class of phosphors as have been described by other researchers. Xu et al. have also reported on this technique for making composite ceramic phosphors, and it appears to be a simpler way of making such phosphors when compared with Czochralski growth.<sup>63</sup> The Chinese group of Zhao et al. have very recently reported that composite ceramic phosphors, where magnesium oxide is used instead of the more common alumina, have superior thermal endurance when compared with alumina-based composites.<sup>64</sup> Also, recently, Hu et al. have shown that composite crystal phosphor can be powdered, mixed with photocurable resin and three-dimensional printed in desired shapes for making specifically structured wavelength down-conversion media.<sup>65</sup>

In the context of LD-excited wavelength up-conversion phosphors, it is important to mention their luminance quenching behavior. It is well-known that over long time intervals, LED-pumped phosphors exhibit a gradual decrease of quantum efficiency. This has reliability implications as well.<sup>66</sup> LED-powered luminaires usually do not fail catastrophically, as tungsten filament lamps do, but gradually diminish in brightness over a long period of time. This is due to various degradation mechanisms—both physical and chemical—that are driven by the operating conditions inherent in phosphor excitation. Apart, from the long duration permanent changes to the phosphor material, reversible reduction in luminance is also seen at much shorter time scales. High temperature-induced thermal quenching is known to be the reason behind this observation. Both LED- and LD-pumped systems exhibit this phenomenon. Care must be taken to limit rise in phosphor temperature, if thermal quenching of luminescence and shift of chromaticity point is to be avoided.<sup>67,68</sup> This is very different for LED- versus LD-based luminaires. In LED-pumped systems, phosphors get heated directly by the somewhat hot LED chip, in addition to non-radiative processes, such as the Stoke's shift. In LD-pumped systems, which almost always employ remote phosphor arrangements, there is no conductive heat transfer from the LD device, but phosphors get heated radiatively from the absorption of some of the incident LD flux. In this case, heating originates from the absorption of part of the pump radiation that is not converted to visible light photons due to inefficiency in the down-conversion process, as well as the self-absorption of a fraction of the down-converted photons.<sup>69,70</sup> The other major contribution to phosphor temperature rise comes from thermal energy production from Stoke's loss, i.e., conversion of the difference in pump and down-converted photon's energy into heat energy. Although, in the case of most LD-pumped luminaires, the LD and the phosphor are spatially



**Fig. 11** Time lag in phosphors' luminescence response for a long persistence phosphor (top) and a shorter persistence phosphor (bottom). The rectangular blue traces are electrical drive waveforms for the pump source in each case.

separate from each other, the sheer optical flux in a collimated narrow diameter beam can very quickly, and significantly, raise phosphor temperature. Thus, thermal luminescence quenching can be a bigger issue with high power LD-pumped systems.

In addition to thermal quenching, LD-pumped systems also show photon fluence quenching, which arises due to the overloading of phosphors with pump photons.<sup>71</sup> Because each luminescent center (luminescent ion) in a phosphor takes a certain time after excitation to decay to its ground level (luminescence decay time), as can be seen in Fig. 11 here, so too many photons arriving together in a limited phosphor volume can result in many being left unabsorbed because luminescent ions are already in their excited state. Short luminescence decay times are, therefore, conducive to reducing photon flux quenching. Fortunately, the widely used YAG:Ce phosphors have short upper state lifetime of around 70 ns, which helps in achieving high optical flux quenching threshold.

Thermoluminescence spectroscopy is a useful technique for investigating the energetics of luminescence decay in phosphor materials.<sup>72-74</sup> Ueda et al. have investigated the thermal luminescence quenching mechanism of YAG:Ce phosphors using thermoluminescence spectroscopy.<sup>75</sup> They maintained different temperatures during the excitation and subsequent luminescent decay of YAG:Ce phosphor samples and studied the decay of thermoluminescence as a function of phosphor temperature. Their results support the hypothesis that it is the thermal ionization of  $\text{Ce}^{3+}$  ion at higher temperatures that reduces wavelength up-conversion luminescence for temperatures above 300°C. Thermally activated photoionization from the upper (5d) levels of  $\text{Ce}^{3+}$  ions into the conduction band of the YAG host, where the electrons get trapped and cannot efficiently return to the lower (4d) level of the  $\text{Ce}^{3+}$  ion, is behind the reduced luminescence intensity seen at higher temperatures.

While thermal quenching of phosphors has been investigated for some time, luminescence quenching due to high photon flux has been properly studied only over the last few years.<sup>76</sup> However, since LD-pumping of phosphors has become more widespread now, this luminescence quenching mechanism is now receiving more attention. The Sino-Japanese collaboration of Zheng et al. has published their findings on this topic where they have attributed photon flux-dependent luminescence quenching on energy transfer up-conversion.<sup>77</sup> This is crucially dependent on the decay time of luminance. Because Ce ions have a much shorter decay time

than Eu ions,<sup>78,79</sup> so cerium-doped phosphors show much less photon flux quenching when compared with europium-doped phosphors. This gives phosphors like YAG:Ce a definite advantage. Very similar conclusions were also reached by Lenef et al.<sup>80</sup>

It should be mentioned in passing that whereas Ce-doped YAG- and YAG-composite-hosted phosphors are the most widely used for LD-pumped applications that require white light, phosphors based on other rare-earth elements have also been tested for this purpose. A dysprosium-doped tellurium-borate glass phosphor for generating white light, for instance, has been described by Li et al.<sup>81</sup> Rare-earth-doped phosphors for generating relatively narrowband colored light with LD excitation have also been developed. In this case, an example is provided by a samarium-doped alkali-alkaline-earth borate glass phosphor, capable of emitting red light with LD pumping.<sup>82</sup> Yet another example is a cerium-doped oxy-nitride phosphor, also for producing red light.<sup>83</sup> Another example is a europium-doped  $\beta$ -sialon phosphor that can produce green light under LD excitation.<sup>84,85</sup> Finally, europium-doped GaN provides a material that can be used as both a pumped conversion medium and an electroluminescent active LED medium for producing red light.<sup>86</sup> All such phosphors are promising for use in RGB systems that require separate narrow wavelength red, green, and blue beams, such as for use in cine projection applications.

#### 4 Future of LD-Powered Solid-State Lighting Technology

At present, laser-pumped white and color light sources are undergoing rapid developments. Their capabilities are now much better understood now than was the case only a few years ago, and this has led to their use in a number of new application areas. Some prominent ones are:

1. Automobile headlamps,
2. Projection and display applications in cinemas and large format televisions,
3. Outdoor architectural lighting,
4. Specialty lighting for scientific applications, spotlights, searchlights, operating theater lights, etc.

While the first LD-pumped luminaires saw their use in automobile headlights, their use has now spread to many more areas. The intense and directional nature of LD radiation confers special capabilities to LD-powered lighting systems, making them especially useful in certain applications that are clearly not as well suited to LED-based systems. One of the most prominent, and now established, uses of LD-excited lamps is in cine projection. Because of the size of cinema screens, very intense light sources are needed in cine projectors. High pressure xenon arc lamps have been traditionally used as light sources in film projectors. These lamps are bulky, fragile, and last for only a few hundred hours before needing to be replaced. Their other drawbacks include possible hazards during installation and removal, and very high thermal loads that require substantial cooling systems. Given such serious shortcomings, it is no wonder that the projection industry has welcomed the advent of alternative solid-state lamps that are superior to xenon lamps in almost every aspect. This market segment is set to see further expansion in the coming years as even smaller home projectors are built with LD-pumped phosphor-converted lamps.

Architectural lighting is an application that demands exceptionally bright light sources. Laser-based phosphor-converted lamps are eminently suitable for this. Multi-laser modules pumping a suitable phosphor sub-system have the power to illuminate entire building facades. By using such light sources, only a few high intensity lamps can light up the exterior of even large buildings. High-power LED module manufacturers are now embracing the use of LDs for making luminaires for architectural lighting, and we are set to see their widespread use within the next few years.

In areas where they serve well, LD-pumped sources are almost always the preferred choice, and this has further spurred their development. As would be expected, their cost has come down substantially over the last few years. Further advances will come from reductions in LD prices, the availability of even higher power LDs, use of LD clusters to boost pump power levels significantly above what can be achieved with a single LD, development of LD-specific phosphors, and advances in system design. New thermal management techniques that can quickly remove

heat from phosphors, as well as the development of high optical damage threshold phosphors will also play crucial roles in the future development of this next-generation light source.

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