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Review Article

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Lighting with laser diodes

Abstract: Contemporary white light-emitting diodes (LEDs) are much more efficient than compact fluorescent lamps and hence are rapidly capturing the market for general illumination. LEDs are also replacing halogen lamps or even newer xenon based lamps in automotive headlamps. Because laser diodes are inherently much brighter and often more efficient than corresponding LEDs, there is great research interest in developing laser diode based illumination systems. Operating at higher current densities and with smaller form factors, laser diodes may outperform LEDs in the future. This article reviews the possibilities and challenges in the integration of visible laser diodes in future illumination systems.

Keywords: headlamp; laser diodes; phosphor; projector; solid state lighting.

OCIS codes: 140.2020; 220.2945; 230.6080.

1 Introduction

Solid-state lighting (SSL) has revolutionized the illumination situation and is steadily progressing in terms of power efficiency and diversity for future applications [1, 2]. White light-emitting diodes (LEDs) are currently widely used in the SSL domain. Most of these white LEDs are basically made of a 445–460 nm blue emitting LED chip with a coating of yellow phosphor. A part of the blue light is absorbed by phosphor which generates a wide range of wavelengths between green and red due to phosphorescence. The combination of the remaining blue component and the frequency down-converted wide spectrum, ranging from green to red, is what we see as 'white' light output from such an LED [3–5]. Laser diodes (LDs) are inherently much brighter than LEDs. In near infrared (NIR), LDs are the most efficient high power sources of photons, in terms of electrical-to-optical power conversion. For example, in 2007, Peters et al. reported high power 940 nm LDs with electrical-to-optical power conversion efficiency as high as 76% [6]. Naturally, there has also been an enormous interest in developing efficient high power LDs operating at visible (RGB) wavelengths. Blue LD and phosphor based white light engines are already integrated in various commercial multimedia projectors [7]. High luminous flux, compact size and low power consumption are very important features for designing light engines for multimedia projectors and automotive headlamps, and hence LDs have an advantage over LEDs in such applications [8]. The first milestone towards blue LD development was achieved by Nakamura with the demonstration of a multi-quantum well (MQW) based InGaN LD operating at violet blue (417 nm) [9]. This LD offered 215 mW of output power under pulsed current (2.3 A, pulse width 2 μs, pulse period 2 ms). Researchers worldwide focused on longer wavelengths towards 'true blue' or 'royal blue' (~445 nm) for digital displays and solid state illumination purposes. In 2009, Michiue et al. reported an LD diode operating at 445 nm with continuous wave (cw) output power of 1.17 W under a steady current of 1.0 A with 4.81 V of bias voltage [10]. With an efficiency of 24.3% and a cw operational lifetime of over 30 000 h, this was an important milestone in high power ~445 nm LD development. Currently, a 445 nm LD (PL TB450) with 1.4 W of output power is commercially available from OSRAM. This particular LD has been recently used in a laboratory prototype of a laser based white light source [11]. It must be noted that the commercial high power (>1 W) 450 nm blue LDs are rather newcomers as compared to the NIR 808 nm or 976 nm LDs and it can be realistically expected that output power as well as efficiency of such blue LDs will increase substantially in the future.

Alternatively, without using any phosphor, an all-laser mixing approach can be selected. There is a misconception

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that laser based light sources may not offer good color rendering due to the inherent narrow linewidth of the laser sources. However, it has been demonstrated, in a four-color laser mixing approach (R, G, B and amber), that the output white light rendered very good colors, contrary to common belief [12]. In this context, true green LD development is also of great importance. Owing to the lack of a true green LD source, most of the green laser pointers (532 nm) have been using a frequency doubled diode pumped solid state (DPSS) architecture so far. Recently, Sumitomo Electric Industries Ltd. and Sony Corp. reported the first true green (530 nm) LD with >100 mW output power [13]. It was also claimed that the 530 nm LD broadened the color gamut by 182% based on the NTSC standard [13]. Naturally, this is a big boost to RGB laser display development.

The basic architecture of a blue LED/LD based white light source using a yellow phosphor is schematically shown in Figure 1. The white light spectrum obtained from a 460 nm LED pumped 5000 K ChromaLit™ remote phosphor module is shown in Figure 2.

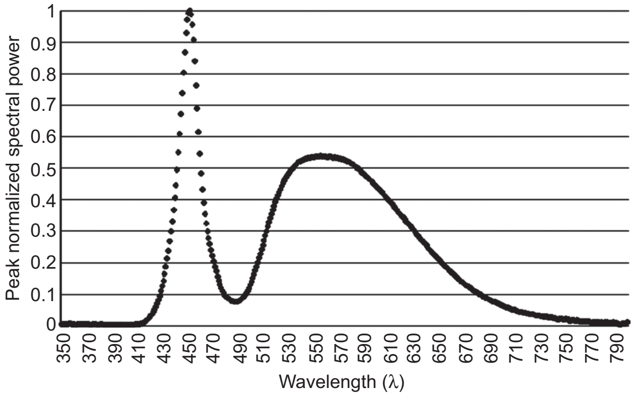

Figure 2 Output spectrum of a 460 nm LED pumped 5000 K ChromaLit™ sample [11].

2 Laser diodes: a brief overview

The demonstration of the first LD dates back to 1962 [14]. Later that year, Nick Holonyak, Jr. demonstrated the first visible LD [15]. An LD is an electrically pumped semiconductor laser. When electrons and holes recombine in the active region, a part of the energy is radiated as photons. Quantum well lasers, distributed feedback lasers and vertical cavity surface-emitting lasers are some of the most popular variants of LDs [16]. There are a few interesting features that make an LD markedly different from an LED. The coated or uncoated end facets of an LD behave like mirrors with different reflectivities, resulting in an effective laser resonator. An LD benefits from the feedback and eventual gain of the stimulated emission of radiation. In comparison, an LED operates with just spontaneous emission of radiation. Note that an LD driven below the threshold current will output just spontaneous emission, much like an LED. LDs offer a wide range of wavelengths, ranging from ultraviolet (UV) to infrared (IR). LDs have found a vast range of applications in the fields of medical science, telecommunication, materials processing, etc. Many other laser systems, such as solid state and fiber lasers, highly depend on diode lasers as optical pump sources. The advancement of high power DPSS lasers and the high power fiber lasers would be unimaginable without the enormous progress in NIR LD technology. The detailed architecture of LDs is beyond the scope of this review. Readers are encouraged to refer to [17] for a detailed discussion on general laser physics, and to [18] for blue LDs and LEDs in particular. A report from DILAS Diodenlaser GmbH on various high power diode laser modules (410–2200 nm) and their opto-electronic characteristics can be found in [19].

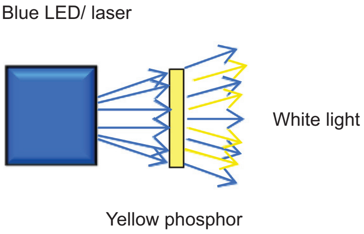

Figure 1 Schematics of a blue LED/LD and phosphor based white light source.

A typical characteristic curve (qualitative) of an LD, showing optical output power (P_{opt}) versus forward current (I_F), is given in Figure 3.

Note that LDs need precision current drivers in order to maintain a good lifetime. LDs often require an active cooling system using a thermo-electric cooler (TEC). Operating an LD at a temperature more than a specified level will shorten the lifetime, which is typically in the range of 10 000–30 000 h. The peak wavelength of an LD is often tunable, in the order of sub-nm, by changing the operating temperature [20]. It should also be noted that threshold current and output power will also change with temperature.

The operating wavelength of an LD mainly depends on the semiconductor material used as the active medium. Laser gain parameters vary with the material used. Hence, it is not easy to have LDs with similar efficiency levels for different operating wavelengths. Cheap red laser pointers

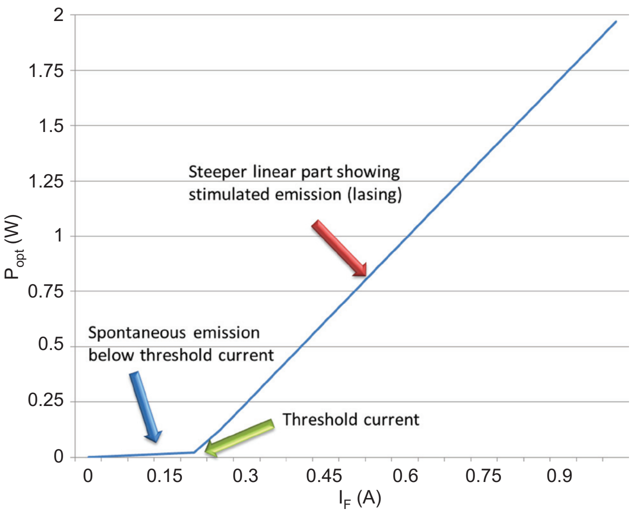

Figure 3 Optical output power versus driving current characteristic of a laser diode.

are usually operating at 670 nm, whereas DVD drives use 657 nm LD modules. Sony reported a 635 nm LD with output power as high as 7.2 W [21]. Keeping in mind the CIE luminosity function (1931), it should be noted that the luminous factor improves significantly [21] as one moves from 670 nm to a shorter 635 nm wavelength, which is highly beneficial for illumination purposes. In 2012, Sharp Corp. reported a 642 nm red LD with 150 mW output power and a wall plug efficiency (WPE) of 33% [22].

As far as a true green laser source is concerned, the >100 mW 530 nm LD from Sony and Sumitomo opened up new possibilities in the laser based display segment [13].

3 Laser beam properties and important lighting applications

A laser beam is a stream of coherent and highly directional photons generated by stimulated emission. Unlike the laser beam, light output from an LED is incoherent and usually has a wide divergence. LEDs emit spontaneously emitted photons which are omnidirectional in nature. Laser beam steering and focusing is much easier than focusing an LED output. The directionality of a laser beam makes it a favorable choice for projection systems and discotheque lightings. Usually, laser beam coupling into an optical fiber is much more efficient than LED beam coupling into the same. LED light coupling requires thicker fibers.

Unlike the light emitted from a typical LED, output from an LD is usually polarized and hence this property can also be suitably exploited in various applications. One can place a light engine with RGB LDs at a hidden location where heat generation can be taken care of and still deliver the coupled light through optical fibers at a desired remote location. This can offer great design flexibility with minimal coupling loss. Alternatively, for example, Harison Toshiba Lighting Corp. demonstrated fiber coupled blue laser engine and phosphor based white light sources at the Light and Building Trade Fair in 2012.

3.1 Automotive

BMW was the first to demonstrate a blue laser based headlamp using remote phosphor in the i8 concept car in 2011 [23]. The system was reported to be much brighter and efficient than LED based counterparts [23]. Furthermore, Audi displayed its laser tail light in the Consumer Electronics Show 2013 [24]. In the Shanghai Motor Show 2013, Mercedes-Benz launched its GLA™ concept sport utility vehicle with a laser projection based front lighting system [25]. Hence, it is evident that the automotive industry is keenly interested in a paradigm shift in its future lighting applications. A smaller form factor of a laser based lamp can offer better design flexibility and more space for the engine and other mechanical components. Note that discomfort glare is a well-known problem in xenon or LED based headlamps and very often it is attributed to the excessive bluish color tone of the light [26]. With the remote phosphor architecture, one can always benefit from the possibility of changing the particular remote phosphor and, as a result, change the color temperature of the output light. Remote phosphors offer exceptional optical design flexibility and thermal management, due to the physical separation of the optical pump source (blue LED/LD) and the phosphor module [27]. In a laser based high power remote phosphor architecture, the LD source and the remote phosphor element can be separately addressed for thermal management. In the case of our headlamp prototype, as reported in [11], the maximum temperature of the remote phosphor at the spot of laser irradiation was measured to be ~47.6°C, and excellent temporal stability of the output luminous flux and correlated color temperature (CCT) were observed. The LD in the prototype was actively cooled by a TEC and the remote phosphor plate, which was in direct contact with air, did not require any special active or passive cooling. Figure 4 shows a part of our latest laser pumped phosphor based headlamp prototype along with the low beam distribution

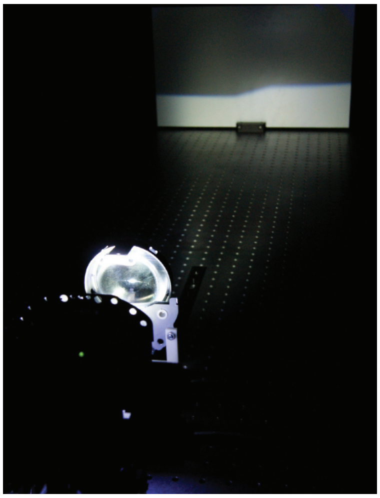

Figure 4 A part of the headlamp prototype along with the low beam pattern formed on a screen.

pattern on a screen. This prototype was developed in collaboration with IPeG, Leibniz University Hannover.

The design aspects of laser pumped remote phosphor based automotive headlamps have been discussed previously in [28].

LDs coupled with diffractive optics elements can generate specific signs (e.g., arrows) or patterns, which can be temporally and dynamically projected at specific locations, as an alert system. Various other applications of such components as functional or design elements are feasible.

3.2 Medical

By launching a laser beam (~450 nm) into an optical fiber, while the other end of the fiber is coated or covered with a suitable yellow phosphor component, white light can be generated and delivered remotely [29]. Such an approach can be utilized in endoscopy offering a compact design [30]. This report [30] also mentioned that such a light source provided more uniform light distribution and sharper image formation than standard endoscope illumination sources. Use of laser beam for such an application would shrink the required fiber diameter considerably in contrast to that in the case of a xenon lamp.

3.3 Projectors

Pico-projectors using tiny RGB LDs and MEMS based two-dimensional (2D) scanning mirrors are already on the market [31–33]. These pico-projectors are mostly limited to approximately 20 lm of output. Recently, Panasonic unveiled a prototype 7.5 mm thick pico-projector with 100 lm output and a resolution of 800×480 pixels. There are also pico-projectors available with RGB LED light engines, but the laser based ones generally offer sharper images on screen, without the requirement of a manual focus dial. Apart from the MEMS 2D scanner, RGB LDs coupled with 'liquid crystal on silicon' (LCOS) microdisplays are also known [34].

There are also standard size projectors with multiple ~450 nm LDs and remote phosphor based light engine replacing traditional projector lamps. Such projectors offer greater power efficiency and longer lifetime than older lamp based projectors. For example, the BenQ® projector LX60ST with a BlueCore™ light engine is claimed to be capable of reducing light source power consumption by up to 90% [7]. The projector datasheet quotes an output of 2000 ANSI lumens, a resolution of 1024×768 pixels and a contrast ratio of 80 000:1 [7].

By contrast, independently controllable RGB laser based light engines for digital projectors have been claimed to offer much higher brightness than typical xenon lamp based cinema projectors [35]. Such a projector system could be especially useful for brighter three-dimensional (3D) cinema projection than the existing ones can offer [36]. IMAX has reportedly invested a huge amount of money in R&D for a laser projection system and expects to improve the contrast ratio from the current (in 2013) 2800:1 to 8000:1 level [37]. Sony Corp., Imax Corp., Barco, Panasonic Corp., Laser Light Engines, Texas Instruments and many others have formed an industry group (http://lipainfo.org/) together in order to advocate formal adaptation of a laser based projection system for large format and 3D cinema screens where conventional light sources do not have much scope to shine any brighter [38]. Given the serious industrial demands and market potential for laser based light engines, it is of great importance to focus on long-term research in this area.

4 Laser speckle reduction

One obvious question that arises while considering laser based illumination is speckle patterns generated due to high spatial coherence. There are several speckle reduction techniques available on the market. However, laser speckle reduction still generates significant research interest worldwide. Use of a standard diffuser to eliminate laser speckles can grossly bring down the efficiency of the system [12]. Hadamard matrices, vibrating reflectors/diffusers [39] or high frequency electronic modulation [40] of the laser sources can be very helpful in order to reduce laser speckles. Some of the handheld multimedia projectors, commonly known as pico-projectors or micro-projectors, use LDs in the respective light engines along with active speckle reduction actuators. The speckle reduction technique used in such actuators differs from product to product [41, 42]. Speckle reduction below the visible level (<10%) has been reported by Lemoptix [42]. Transmissive speckle reduction elements are also commercially available [43]. The optimal selection of the speckle reduction technique for any laser based lighting system will significantly depend on the LD output power, beam size and the power consumption of the actuator itself.

5 System efficacy

The market potential of any light source hugely depends on the overall luminous efficacy (LE), in simple words, the ratio of the output lumens and the input electric power. As a simple example, one can consider a 100 W incandescent lamp delivering approximately 1700 lm, amounting to an LE of 17 lm/W and a fluorescent tube light offering approximately 80–110 lm/W [44, 45]. The latest 2013 catalog from CREE® reports white LED based lamps (catalog products) with LE of 130 lm/W. Philips has reported its R&D prototype TLED™ lamps, using red and blue LEDs along with an optimized green phosphor, with an LE of ~200 lm/W [45]. Hence, for any diode laser based lamp system to be commercially viable, such high or even better LE levels will have to be achieved. However, readers should carefully note that many of the high LE white LEDs offer 'warm white' or yellowish light output that may not be suitable for a variety of illumination conditions.

In a note by BMW on their laser based headlamp system, 170 lm/W of LE was reported [46]. However, to the best of our knowledge, the details of the LDs used, including the WPE, are unknown in the public domain so far.

In the context of power consumption and environmental impact, readers are encouraged to read a report on LED lighting products for a broader overview [47].

6 Operating lifetime

LDs are known to have a typical lifetime of tens of thousands of hours under standard operating conditions. For example, the OSRAM PL TB450 LD is quoted to have a lifetime of 10 000 h at 40°C in continuous operation [48]. It must be noted that the lifetime of an LD strongly depends on the temperature and the stability of the electrical power source. Subjecting an LD to a higher-than-recommended temperature or using a noisy current source can seriously shorten the lifetime or totally damage it. A technical note on the estimation of LD lifetimes can be found in [49]. It is worth mentioning here that in a laser pumped remote phosphor based system, the lifetime of the system will be mainly determined by the lifetime of the pump LD as the remote phosphors available at present can offer an expected lifetime of 50 000 h [50]. Note that royal blue LEDs are also known to have tens of thousands of hours of lifetime. While comparing the lifetime of different SSL sources, it is very important to highlight the suggested guidelines and measurement procedure used in each case [51].

7 CER, WPE, LER and LE

While using a blue source pumped phosphor system, the conversion efficacy of radiation (CER) or simply conversion efficacy is defined as the total amount of lumens generated per unit optical power (W) irradiated by the blue source (LD or LED). Hence, CER is expressed in terms of $\mathrm{lm/W_{rad}}$. The ChromaLit™ product datasheet mentions typical CER of 218 lm/W and 230 lm/W for the 4000 K and 5000 K ChromaLit™ remote phosphor plates, respectively [52]. In recent experiments with a 447 nm blue LD source and ChromaLit™ remote phosphors, CER values as high as 235 lm/W and 249 lm/W for the 4000 K and 5000 K ChromaLit™ samples were measured [11]. These numbers are emphasized here in order to provide a general idea about the typical CER values obtainable with blue LD or LED pumped commercial remote phosphor modules. Note that the ChromaLit™ catalog products we used were not specifically designed for laser pumped applications, and hence further optimization could be possible. The CER values are of practical importance to those working with ~450 nm LDs and remote phosphor systems, in order to quickly estimate the amount of lumens that can be generated from a remote phosphor pumped by a blue LD with a certain optical output power (W). Of course, one should note that the overall lumens generated by such a system will also depend on the mixing chamber design, peak pump wavelength and the pump spectral distribution.

An extremely important characterization parameter for illumination sources is the luminous efficacy of radiation (LER) or spectral luminous efficacy. Mathematically, LER can be written as follows:

$$LER = 683\,(\mathrm{lm/W})\,\frac{\int_0^\infty V(\lambda)s(\lambda)d\lambda}{\int_0^\infty s(\lambda)d\lambda}$$

where $V(\lambda)$ is the CIE luminosity function (1931) and $s(\lambda)$ is the spectral distribution. By definition, the constant, 683 (lm/W), represents the maximum LER possible for a monochromatic source at 555 nm. Note that an ideal human eye is most sensitive at 555 nm. It is evident from the LER expression for a source that the electromagnetic spectral power distribution $s(\lambda)$ spreading outside the range of $V(\lambda)$, 380–780 nm, will reduce the LER accordingly.

It is reported that any practical white light source confining its spectrum to the visible wavelengths is likely to achieve an LER of 250–350 lm/W [53]. Analytical calculations of spectral power distribution required for maximum LE of radiation at given color rendering index (CRI) and CCT have recently been reported [54].

However, the overall LE of the system will be hugely dependent on the WPE of the blue source (LD or LED). WPE is defined as the output optical power per unit input electric power. The LE of the system, assuming no other losses, can be written as $LE=WPE\times CER$. If we define efficiency ($\eta_{phosphor}$) of the remote phosphor as the output radiant flux (watt) obtained per unit input radiant flux (watt), we may express LE also as $LE=\eta_{phosphor}\times WPE\times LER$. Hence, $CER=\eta_{phosphor}\times LER$.

For a practical overview, one can experimentally compare the WPE of the leading commercial royal blue/deep blue (~440–460 nm) LEDs with the LE of ultra-bright white LEDs, measured at different color temperature levels separately. It is extremely difficult to compare the WPE of blue/royal blue/deep blue LEDs and the LE of white LEDs from different manufacturers' datasheets as the values mentioned therein are often measured at lower current levels than the suggested operating current levels. LEDs are prone to the well-known 'efficiency droop' at higher current levels and hence the maximum radiant flux (W) or lumens (lm) advertised or specified for an LED may not be at the optimal point of efficiency. Such a droop in the quantum efficiency of InGaN LEDs at high current densities might be attributed to Auger recombination of carriers [55]. An InGaN blue LD based white light source has demonstrated nearly droop-free performance as compared to a white LED [56]. It is worth mentioning here that LDs can operate at much higher current densities (1–10 kA/cm^2) than LEDs (10–100 A/cm^2) [56]. Thus, it can be argued that for brighter and high power applications LDs will possibly move up the performance ladder from where LEDs stop. LDs will also benefit from a smaller form factor than comparable LEDs.

The OSRAM PL TB450 LD used in our recent experiments offered more than 25% WPE while operating at the specified ~1.4 W output level with the TEC temperature set to 15°C [11]. To validate our results, we noted that the OSRAM product release note quoted 27% WPE while generating 1.4 W of output power at room temperature and a current of 1.2 A [48]. At present, to the best of our knowledge, there is no blue LD with WPE greater than or even close to that of the commercial royal blue LEDs (Cree® XLamp® XT-E) offering WPE >50% [57]. It is worth mentioning here that the InGaN based MQW blue LD technology is not as mature as that of its NIR counterparts such as 808 nm, 915 nm or 976 nm LDs. For example, a particular 975 nm LD can generate 25 W of output at approximately 54.6 W of input electrical power, leading to ~46% WPE [58].

In an article on InGaN based blue LDs by Soraa Inc., an increase in WPE from ~1% to over 23%, within the period between April 2009 and June 2010, while the output power increased to over 750 mW, was reported [59]. In May 2011, Soraa Inc. reportedly achieved a maximum output power >1.4 W with WPE >21% [59]. Such a trend is very promising for practical applications of laser pumped phosphor systems in the near future.

8 Quality of color rendering and CRI

Color rendering quality is one of the most important features of any illumination source. Any light source which apparently looks like delivering white light may not render natural colors to the object under illumination. This is often the case with phosphor based white LEDs. CRI is the standard metric, which is used to define the color rendering quality of a light source [60]. CRI has a scale of 0–100 where 100 denotes the best color rendering. Sunlight (daylight) has a CRI of 100. SSL is often reported of having poor color rendering qualities. In the case of a phosphor based system, quality of light can be improved by choosing the right phosphor component [61]. By contrast, the shortcomings of using CRI for characterizing SSL sources such as LEDs have been pointed out by some researchers [62]. In fact, the National Institutes of Standards and Technology has proposed an alternative metric, the color quality scale (CQS) [63]. Hence, there is a possibility that different metric(s) for SSL color quality characterization will be introduced in the future. Such metrics could also be beneficial for characterizing LD pumped remote phosphor based systems. One particular study has pointed out the need for reliable information on a plethora of consumer grade SSL products in terms of CCT, CRI, efficacy, etc. [64]. The trade-off between CRI and LE has also been emphasized in this study.

The color rendering qualities of various light sources such as tungsten halogen, xenon, fluorescent lamp, LED and our laser pumped remote phosphor based headlamp prototype have been compared by taking digital snapshots of a set of colorful fruits illuminated by the aforementioned sources [11]. Interestingly, color rendering by our laser pumped phosphor based headlamp prototype looked better than that by a commercial xenon headlamp. The chromaticity coordinates of our laser pumped remote phosphor based light source were shown to be within the 'white color space – UN/ECE R48 (2.29.1)'.

9 Cost

Cost is an extremely important factor in determining the viability of any SSL product. At present, LDs are more expensive than LEDs with comparable output power. As a simple example, the OSRAM OSLON 461 nm blue LED (LD CQ7P-1U3U-W5-1) with 1219 mW output power at 1000 mA current and 3.5 V of forward bias voltage is priced at around €2 on the market [65]. In contrast to this, the OSRAM 1.4 W royal blue LD (PL TB450) is available on the market at a price of approximately €100 [66]. Hence, it is fair to say that, for general lighting applications, LEDs will have an advantage over LDs as far as cost is concerned. However, when the applications are demanding enough to exploit the extraordinary qualities of lasers such as high brightness, collimated beam propagation, compact size, etc., a steady progress of LD based lighting systems is highly expected.

10 Laser safety and compliance

Lasers are not like ordinary light source and strict adherence to safety norms is a must for any consumer grade light source development. Moderate and high power lasers can irreversibly damage the human eye and even burn skin. Anyone handling laser products should carefully go through the relevant safety instructions. As a general reference, the international safety standard IEC 60825 Ed. 2 (2007) can be followed. For blue laser pumped phosphor based systems, the white light output is highly divergent and no longer as collimated as the input blue laser beam. In fact, phosphorescence is omnidirectional. Thus, the brightness (power emitted per unit surface area per unit solid angle) of such a white light source can be much lower than that of a laser. Note that the term 'brightness' is widely used in laser physics and this is the same as radiance.

Another important aspect to be considered is the generation of speckle patterns due to high coherence of lasers. Laser speckles in the illuminated area can be visually disturbing and should also be considered as a safety issue [67]. It has been shown that with proper engineering design, a laser pumped phosphor based system at 5000 lm output could suppress the speckle contrast to as low as 1.7%, similar to that of a blue LED [68]. Such a design may entitle a laser based light system to be compliant with the IEC 62471 standard and categorized as a lamp [68, 69].

While using RGB laser sources in scanning type projector systems, active speckle reduction techniques should be applied. In the case where the scanning actuator fails to move, an additional safety mechanism should be able to immediately shut down the laser sources, in order to avoid the emission of a collimated bright beam fixed to a certain direction.

11 Summary and conclusions

Utilization of visible LDs in a wide range of lighting applications has been reviewed in this article. Possibilities of future commercial and consumer applications are also discussed. Besides the applications already mentioned, future applications of visible LDs may extend to areas as diverse as illumination for greenhouses and fisheries. In this review, a direct comparison of LDs with LEDs has been frequently made for a better understanding of the topic. The unmatchable qualities of laser sources, as compared to LEDs, have been discussed. Some of the latest LD based products have been referenced along with a significant number of relevant scientific publications. Our own experimental results, obtained from a 1.4 W LD pumped remote phosphor based headlamp prototype with good thermal stability, are also mentioned. Note that, in future, blue laser sources with tens of watts of output power might require both physical and chemical design optimization of the remote phosphors, in order to achieve good thermal management. This review emphasizes on our strong conviction that LD based lighting systems will play a huge role in shaping the future of SSL, especially in high power applications.

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References

[1] J. Y. Tsao, J. J. Wierer Jr., L. E. S. Rohwer, M. E. Coltrin, M. H. Crawford, et al., Topics Appl. Phys. 126, 11–26 (2013).

[2] S. P. DenBaars, D. Feezell, K. Kelchner, S. Pimputkar, C.-C. Pan, et al., Acta Mater. 61, 945–951 (2013).

[3] N. C. George, K. A. Denault and R. Seshadri, Annu. Rev. Mater. Res. 43, 2.1–2.21 (2013).

[4] L. Chen, C. C. Lin, C. W. Yeh and R. S. Liu, Materials 3, 2172–2195 (2010).

[5] Y. Narukawa, M. Ichikawa, D. Sanga, M. Sano and T. Mukai, J. Phys. D Appl. Phys. 43, 354002 (6 pages) (2010).

[6] M. Peters, V. Rossin, M. Everett and E. Zucker, Proc. SPIE 6456, 64560G-1–11 (2007).

[7] http://www.benq.com/product/projector/lx60st/.

[8] R. Hashimoto, H. Hung, J. Hwang, S. Saito and S. Nunoue, Opt. Rev. 19, 412–414 (2012).

[9] S. Nakamura, M. Senoh, S.-I. Nagahama, N. Iwasa, T. Yamada, et al., Jpn. J. Appl. Phys. 35, L74–L76 (1996).

[10] A. Michiue, T. Kozaki, T. Yanamoto, S.-I. Nagahama and T. Mukai, IEICE Trans. Electron. 2009, 194–197 (2009).

[11] C. Basu, G. Kloppenburg, A. Wolf, M. M. Wollweber, B. Roth, et al. (accepted contribution for the International Symposium on Automotive Lighting 2013 to be held in Darmstadt, Germany in September 2013).

[12] A. Neumann, J. J. Wierer, W. Davis, Y. Ohno, S. R. J. Brueck, et al., Opt. Expr. 19, A982–A990 (2011).

[13] http://www.photonics.com/Article.aspx?AID=51189.

[14] R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys and R. O. Carlson, Phys. Rev. Lett. 9, 366–368 (1962).

[15] N. Holonyak and S. F. Bevacqua, Appl. Phys. Lett. 1, 82–83 (1962).

[16] http://www.thorlabs.com/tutorials.cfm?tabID=26065.

[17] A. E. Siegman, in ‘Lasers’, ISBN-10-0935702113 (University Science Books, 1986) pp. 1283.

[18] S. Nakamura, in ‘Introduction to Nitride Semiconductor Blue Lasers and Light Emitting Diodes’, ISBN-10-0748408363 (CRC Press, 2000) pp. 386.

[19] B. Köhler, H. Kissel, M. Flament, P. Wolf, T. Brand, et al., Proc. SPIE 7583, 75830F-1–13 (2010).

[20] J. Bartl, R. Fíra and V. Jacko, Meas. Sci. Rev. 2, 9–15 (2002).

[21] http://www.sony.net/Products/SC-HP/cx_news/vol55/pdf/sideview55.pdf.

[22] http://www.laserfocusworld.com/articles/2012/12/sharp-to-market-red-laser-diode-with-high-wall-plug-efficiency.html.

[23] http://wot.motortrend.com/bmw-shows-us-how-its-laser-headlights-and-dynamic-lightspot-work-126103.html.

[24] http://wot.motortrend.com/audi-debuts-laser-taillights-in-car-lte-connectivity-3-d-displays-at-2013-ces-311529.html.

[25] http://www.engadget.com/2013/04/18/mercedes-benz-gla-concept-puts-laser-projectors-in-headlights.

[26] M. Sivak, B. Schoettle, T. Minoda and M. J. Flannagan, in ‘Blue Content of LED Headlamps and Discomfort Glare’, UMTRI 2005-2. Available at: http://deepblue.lib.umich.edu/bitstream/handle/2027.42/57444/98625.pdf?sequence=1.

[27] M. Jansen, Comp. Semiconduct. 18, 37–41 (2012).

[28] G. Kloppenburg and R. Lachmayer, in ‘Development of a Laser Headlight’, 13th International Conference: Intelligent Automotive Lighting 2013, Wiesbaden 28–30, January 2013.

[29] http://www.photonics4life.eu/P4L/Research/Local-Cluster-Projects/Laser-pumped-endoscopic-illumination-source.

[30] V. J. Nadeau, D. S. Elson, M. A. Neil and G. B. Hanna, Conf. Proc. IEEE Eng. Med. Biol. Soc. 2008, 2059–2062 (2008).

[31] http://www.aaxatech.com/products/l1_laser_pico_projector.htm.

[32] http://www.microvision.com/technology/pdf/OPN_Article.pdf.

[33] http://www.projectorcentral.com/aaxa_l1_laser_pico_projector_review.htm.

[34] K. M. Guttag, S. Hurley and B. Mei, in ‘Distinguished Paper: Laser+LCOS Technology Revolution 2011: SID Symposium Digest of Technical Papers’, vol. 42, 536–539 (2011).

[35] http://www.laserlightengines.com/company.php.

[36] http://www.laserlightengines.com/why-side-by-side.php.

[37] http://www.pocket-lint.com/news/120059-imax-interview-future-cinema-brian-bonnick.

[38] http://online.wsj.com/article/SB20001424052748703376504575491771830240594.html.

[39] K. Ø. Apeland, ‘Reduction of speckle contrast in HDTV laser projection display’ (Master thesis, Norwegian University of Science and Technology, 2008).

[40] Schäfter+Kirchoff catalogue 2013 E, p. 61.

[41] http://www.dyoptyka.com/publications/Dyoptyka-PW-8252-4-updated.pdf.

[42] http://www.lemoptix.com/applications/microprojection/mobile-devices/.

[43] www.optotune.com.

[44] A. H. Rosenfeld and L. Price, Chapter 7, in ‘Plasma Science and the Environment’, ISBN-10-1563963779 (AIP Press, 1996) pp. 250.

[45] http://www.newscenter.philips.com/main/standard/news/articles/20130411-details-of-the-200lm-w-tled-lighting-technology-breakthrough-unraveled.wpd.

[46] http://www.bmwusanews.com/print.do;jsessionid=DAC82F8C9BC423C0D63B80E84E08F176?&id=766.

[47] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/2012_LED_Lifecycle_Report.pdf.

[48] http://www.osram-os.com/osram_os/en/press/press-releases/ir-devices-and-laser-diodes/2012/blue-laser-diode/index.jsp?mkturl=pr-bluelaser.

[49] http://assets.newport.com/webDocuments-EN/images/AN33_Laser_Diode_Activation_IX.pdf.

[50] http://www.lumaera.com/wp-content/uploads/2013/04/LUMAERA-50-RP.pdf.

[51] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide.pdf.

[52] http://www.intematix.com/products/ChromaLit/ChromaLit-specifications.

[53] T. W. Murphy, J. Appl. Phys. 111, 104909 (6 pages) (2012).

[54] P. C. Hung and J. Y. Tsao, J. Display Technol. 9, 405–412 (2013).

[55] J. Iveland, L. Martinelli, J. Peretti, J. S. Speck and C. Weisbuch, Phys. Rev. Lett. 110, 177406 (5 pages) (2013).

[56] S. DenBaars, S. Nakamura and J. S. Speck, in ‘SIECPC Invited Talk’, April 28 2013, pp. 33 (slides). Available at: http://www.kacst-siecpc.org/2013/en/images/speakers/pdf/Invited/photonics/phot_spk1_DenBaars.pdf.

[57] http://www.cree.com/~/media/Files/Cree/LED%20Components%20and%20Modules/XLamp/Data%20and%20Binning/XLampXTE.pdf.

[58] Oclaro laser diode BMU25A-975-01-R03. Available at: http://www.oclaro.com/datasheets/D00438-PB_BMU25A-9xx-01-R03_Iss04_Datasheet.pdf.

[59] J. W. Raring, M. C. Schmidt, C. Poblenz, Y. Lin, C. Bai, et al., Recent progress in InGaN-based laser diodes fabricated on nonpolar/semipolar substrates, WN1, Photonics Conference (PHO) – IEEE, October 2011, Arlington, VA, USA. Available at: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6110781.

[60] http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led-color-characteristics-factsheet.pdf.

[61] D. O'Hare and J. H. Melman, in 'LED Professional Review', vol. 34 (2011).

[62] Y. Ohno, Proc. SPIE 5530, 88–98 (2004).

[63] http://www.nist.gov/pml/div685/high/highlight_jul10.cfm.

[64] C. Dam-Hansen, D. D. Corell, A. Thorseth and P. B. Poulsen, Proc. SPIE 8641, 864119 (10 pages) (2013).

[65] http://de.rs-online.com/.

[66] http://www.lasershop.de/Laserquellen/Laserdioden/OSRAM-Blaue-Laserdiode-450nm-1-4W-PL-TB450.html.

[67] D. L. Fried, J. Opt. Soc. Am. 71, 914–916 (1981).

[68] J. Kinoshita, Y. Ikeda, Y. Takeda, M. Ueno, Y. Kawasaki, et al., Opt. Rev. 19, 427–431 (2012).

[69] IEC62471 Standard, Ed. 1.0 (2006).

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