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Blue Laser Diode-Based Visible Light Communication and Solid-State Lighting

Amjad Ali, Qian Li, Hongyan Fu and Syed Raza Mehdi

Abstract

In this chapter, we review our recent work on blue laser diode-based visible light communication and solid-state lighting. Gallium nitride (GaN) phosphor-converted white light-emitting diodes (Pc-WLEDs) are emerging as an indispensable solid-state lighting (SSL) source for next-generation display system and the lighting industry. Together with the function of lighting, visible light communication (VLC) using Pc-WLEDs has gained increasing attention to fulfill the growing demand for wireless data communication. Practically, the low modulation response and low emitting intensity of light-emitting diodes (LED) are the drawbacks for the development of ultrahigh-speed VLC and high-quality SSL system. Blue GaN laser diode (LD) and remote phosphor-based white light can be used for both high-speed VLC and SSL simultaneously. We demonstrated a color-rendering index (CRI) of 93.8, a correlated color temperature (CCT) of 4435 K, and a data rate of 1.6 Gbps under NRZ-OOK modulation by an exciting blue laser diode on narrowband green-/red-emitting composite phosphor film. This work opens up exciting possibilities for future high-speed indoor VLC and high-quality SSL.

Keywords: laser diode, phosphor, visible light communication, solid-state lighting

1. Introduction

1.1 Visible light communication (VLC)

Visible light communication (VLC) is an emerging technology that is intended to enable high-speed data transmission. It operates in visible band (390 nm–700 nm) and uses an LED or LD as a transmitter. The bandwidth available in the visible light spectrum is 390 THz, which is 1300 times greater than the bandwidth of radio frequency (RF) shared by many applications [1, 2]. The massive increase of mobile data traffic leads to saturation of the available RF communication bandwidth, which leads to a decrease in the quality of service. Considering the saturation of RF communication bandwidth, a complementary solution is required. VLC is one of the most promising alternative candidates to provide an additional spectrum. It simultaneously offers illumination, communication, and localization [3, 4]. In 5G/6G communication, the VLC system is one of the forthcoming candidates for indoor wireless access. It offers several advantages over existing wireless communication systems, such as high bandwidth, worldwide availability, network

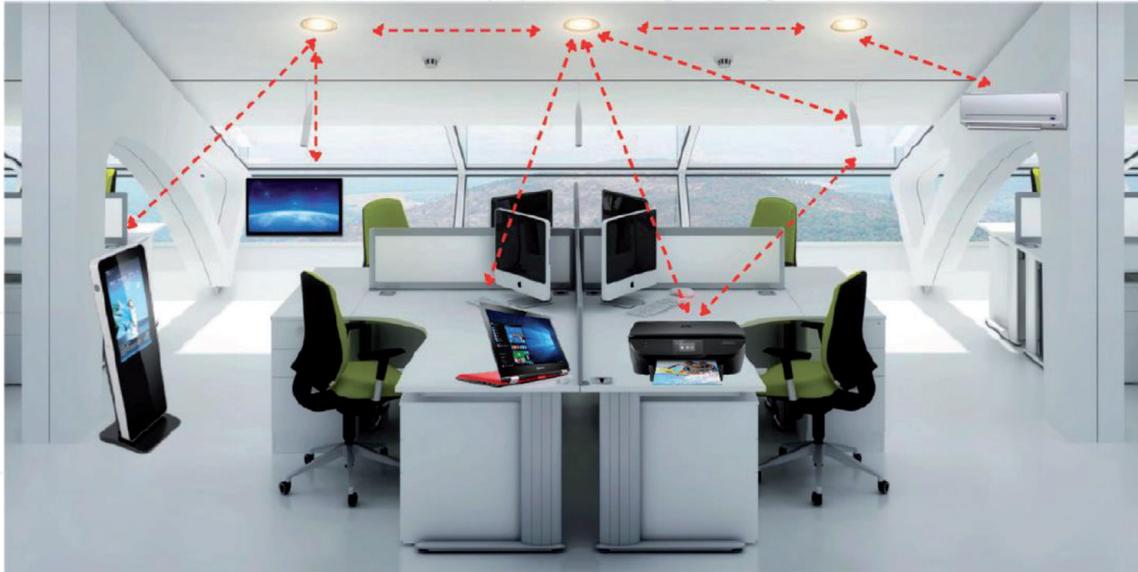


Figure 1.
The possible application scenarios of VLC [9].

security, and unlicensed bands. VLC satisfies the growing demand for wireless data communication. Therefore, it has been proposed to be used in vehicle-to-vehicle communication [5], indoor communication [6], wireless local area networks, wireless personal area networks, and underwater wireless optical communication (UWOC) [7, 8]. The possible application scenario of VLC is shown in **Figure 1**.

1.2 Solid-state lighting (SSL)

Solid-state lighting (SSL) is a technology in which semiconductor material converts electricity into visible light [10]. Such technology produces visible light utilizing the principle of electroluminescence (EL). EL is a phenomenon in which semiconductors emit light when an electric current pass through them. SSL technology generates visible light with reduced heat generation and less energy dissipation as compared to the traditional lighting sources. Over the past few years, SSL attracted much attention for general lighting than conventional light sources due to their advantages: small size, long lifetime, lower energy consumption, high efficiency, high color rendering index, high luminous efficacy, and environmental friendliness. According to the U.S. Department of Energy (DOE), by 2035, SSL will penetrate over 90% market and reduce lighting energy consumption by 75% [10].

2. Optical transmitters

One of the critical components in VLC and SSL to achieve high data rate data link and high CRI lighting is the optical transmitter. The modulated electrical signal is applied to the transmitter. The transmitter usually consists of LED and LD to convert the electrical signal to an optical signal. Further optical elements and color converter phosphor can be used to control the shape and color of the emitted light beam, respectively. The transmitter's capabilities are usually determined by its design. In VLC and SSL promising light source requires high energy conversion efficiency, large modulation bandwidth, high light output power, low operating voltage, small foot print and long lifetime. Practically, the low modulation response and low emitting intensity of LED are the drawbacks for the development of ultrahigh-speed VLC and high-quality SSL system. Blue gallium nitride (GaN) laser

Parameters	Light emitting diode	Laser diode
Working operation	Spontaneous emission.	Stimulated emission.
Bias/Current	It requires small applied bias and operates under relatively low current densities.	It requires high driving power and high injected current density is needed.
Coupled power	Moderate	High
Ease of use	Easier	Harder
Spectral width	Wider, 25 to 100 nm (10 to 50 THz)	Narrower, <10–5 to 5 nm (<1 MHz to 2 MHz)
Modulation Bandwidth	Moderate, Tens of KHz to tens of MHz	High, Tens of MHz to tens of GHz
E/O Conversion Efficiency	10 to 20%	30 to 70%
Eye Safety	Generally considered eye-safe	Must be rendered eye-safe, especially for $\lambda < 1400$ nm
Cost	Low	Moderate to High

Table 1.
Specification difference between LED and LD [11].

diode (LD) and remote phosphor based generated white light can be used for both high-speed VLC and SSL simultaneously. The specification difference between LED and LD is shown in **Table 1**.

3. Strategies for generating white light from laser diodes

Generally, there are three strategies for generating white light from laser diodes (LDs).

3.1 Multiple LD's chips

White light can be generated by mixing light from three individual (red, green, and blue) LDs. The luminous efficacy of generated white light is relatively higher because of the absence of conversion phosphors and quantum deficits. Color variations with temperature can be observed because each LD's wavelength shift may differ with temperature changing. Because multiple LDs are used in this scheme, it is relatively expensive and complex.

3.2 Blue LD chip and color conversion phosphors

White light can be generated by using a blue LD to excite remote phosphor film composed of green and red-emitting phosphors. The mixture of the residual blue light and emitted red and green lights forms a white light. The green and red-emitting phosphors can have broad emission wavelength ranges, which helps generate high CRI white light. An enormous loss of energy occurs in converting the blue light into green and red through the phosphors.

3.3 UV LD chip and RGB phosphor

White light can be generated by using ultraviolet (UV)-LD to excites RGB emitting phosphors. The mixture of emitted blue, green, and red lights results

in white light to human eyes. High CRI white light can be generated using this method because the red, green, and blue phosphors emission can cover the whole visible region. When the UV radiation is down-converted into the visible light, there is a large loss of energy, therefore the luminous efficacy of this scheme is low.

4. Laser diode-based solid-state lighting

Blue GaN LD is an emerging candidate in the future high-luminance SSL because of its advantages over the LED and traditional lighting sources. The higher efficiency of LD at higher current densities makes LD an alternative promising excitation source for higher-luminance SSL application. The LD light source has the potential to generate more efficient white light as compared to LED. LD has high coherence, high power per unit area, and narrow spectral width. Recently the attention of the researchers shifted towards LD-based phosphor-converted white light source. Different types of phosphor films have been previously reported to generate LD-based white light in SSL. For example, in 2008, Xu Yun et al. generated a UV GaN LD-based white light source of 5.7 lm with a CRI of 70 and a CCT of 5200 K by using strontium halophosphate activated with divalent europium as a blue phosphor, and a YAG as a yellow phosphor [12]. In 2009, the same research group generated white light of 3.6 lm with CCT of 5393 by exciting near-UV laser diode on red-, green-, and blue-emitting phosphors [13]. In 2010, white light emission of 5 lm with an efficacy of 10 lm/W by exciting 445 nm blue LD on Eu-doped silicate $[(\text{BaSr})_2\text{SiO}_4 : \text{Eu}^{2+}]$ yellow phosphor is reported [14]. Kristin et al. generated a white light of 252 lm with a CCT of 400 K and a CRI of 57 using blue LD in combination with yellow-emitting cerium-substituted yttrium aluminum garnet (YAG: Ce) [15].

4.1 Advantages of LD based SSL

4.1.1 Efficiency

LED is an excellent energy-efficient light source for artificial lighting applications. Despite the outstanding achievement, LED still has drawbacks. The efficiency of LED drops at high current densities, limiting the luminous flux per unit area of an LED chip. The comparison of efficiency versus input current density

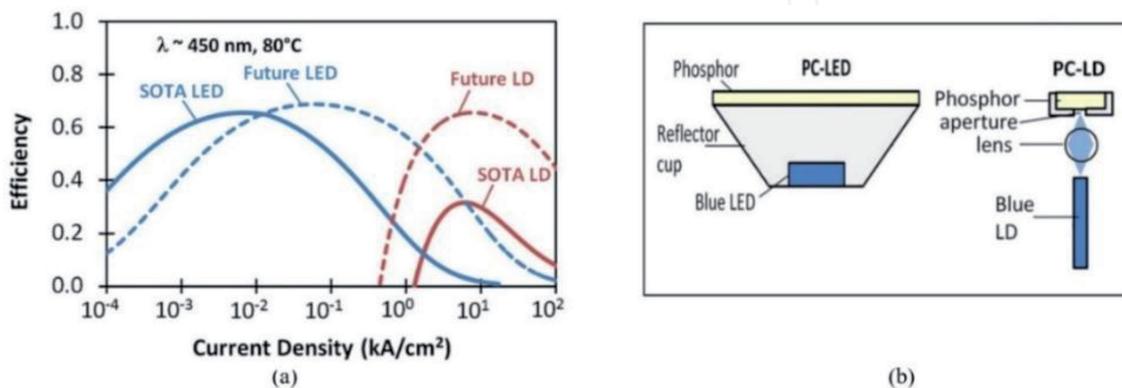


Figure 2.

(a) The comparison of the efficiency versus input current density between state-of-the-art and future LEDs and LDs. (b) The comparison of the area of PC-LED and PC-LD phosphor film [16].

between LEDs and LDs are shown in **Figure 2(a)**. The efficiency of LEDs is high at a relatively low input current density and decreases with the increasing input current density. In contrast to LEDs, the LDs efficiency is low at low input current density and keeps rising with input current density after threshold current. At higher current densities, the efficiency of the LDs eventually drops because of resistivity loss.

4.1.2 LD's directional emission

The directional emission beam with a small divergent angle of LD can be easily collected and focused on phosphor film compared to the LED's Lambertian emission, as shown in **Figure 2(b)**. LD's etendue is very small and can achieve high-luminance lighting; hence, LD can be used in automotive lighting. Bayerische Motoren Werke (BMW) proposed a headlamp by exciting blue LD on remote phosphor film. It was reported that the efficiency and brightness of LD-based headlamp are higher than LED-based headlamp [17]. LD-based headlamp can project the high luminescent, low divergent white beam to half-mile from the vehicles. The laser beam's visual range is 600 m, while that of the LED is 300 m [18]. In the case of LD-based SSL, a small phosphor area and small lens are required; thus, generated light can be more efficiently coupled into an optical fiber and used for micro luminaires.

4.1.3 Narrow spectral width

The emission spectrum of the LED and LD is shown in **Figure 3**. The full width half maximum (FWHM) of the LED is 20 nm, while that of LD is 2.5 nm. In the illumination process, the spectral width reflects the color purity of the generated light. The requirements on spectral width are slightly different in different areas. In the LED-backlit display, the spectral width is the smaller the better, which leads to a purer emitted light color and is useful for color matching.

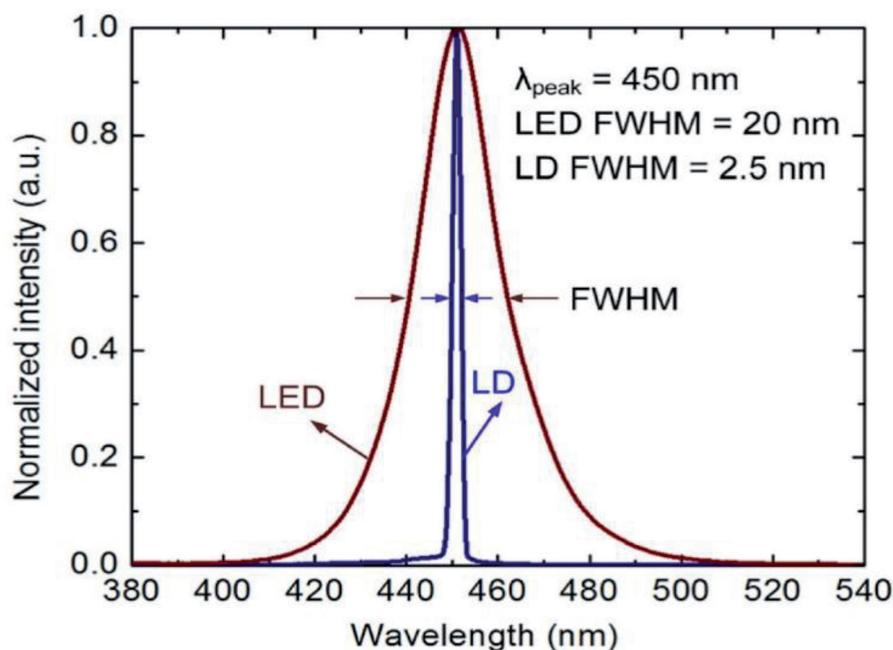


Figure 3.
The emission spectrum of LED and LD [19].

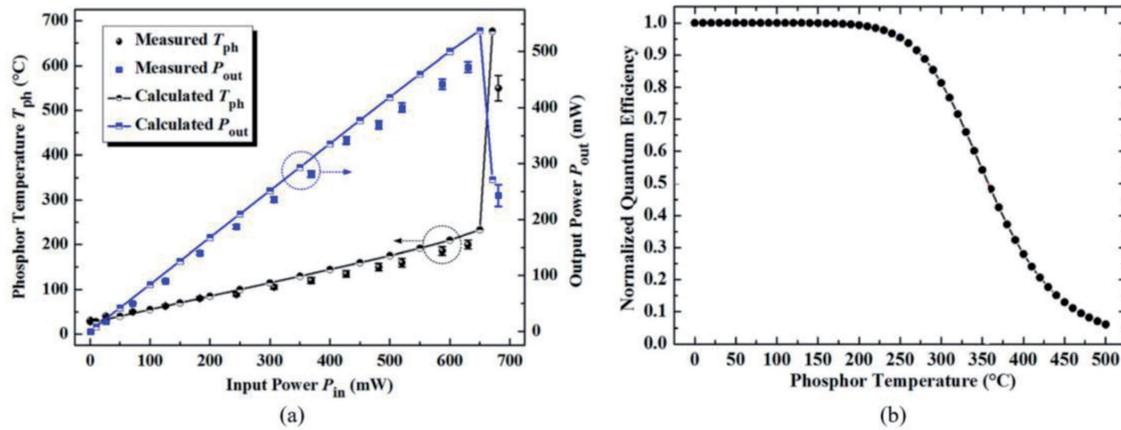


Figure 4.

(a) The phosphor temperature and output power versus input currents. (b) Quantum efficiency versus phosphor temperatures of commercially available phosphor YAG: Ce [19].

4.2 Disadvantages of LD based SSL

4.2.1 Saturation and heat

The phosphor film heats up when an intense light from an LD penetrates through it. The phosphor temperature and output power versus input current are shown in **Figure 4(a)**. It can be seen that after the input power exceeds the critical value, the temperature of phosphor suddenly increases while the output power decreases. The part of optical energy is converted into heat due to quantum efficiency loss and stock shift loss. This heat can cause the limitation of the lifetime of phosphor and thermal quenching. The quantum efficiency versus phosphor temperature of commercially available phosphor YAG: Ce is shown in **Figure 4(b)**. As the temperature increases, the QE remains stable, and above a certain temperature, the QE starts decreasing.

4.2.2 Speckle

The laser light is highly coherent and thus can induce speckles. In LD-based white light, speckles are inherent due to the residual pump source, which degrades the contrast and visual definition. Luminaires that use powder phosphor exhibit less speckles than single crystal phosphor because multiple light scatterings occur in powder phosphor, destroying the optical coherence. Hence, powdered phosphor-based light exhibits little speckles. The speckles can be reduced by using a rotating diffuser and light-diffusing membranes.

5. Color conversion phosphors

Commercial, industrial, and residential lighting are promptly shifting towards a phosphor-converted white light system. The most preferred way to generate white light from LEDs/LDs is to use phosphors that have the ability to absorb the high energy (short wavelength) photons and down-convert them into lower energy (longer wavelength) ones. The chemical composition of phosphor plays an essential role in display, SSL, and VLC. In the 19th century, phosphor's name arose as a generic term for a material that glows in the dark. Phosphor is a kind of photoluminescent material that emits visible light when exposed to certain radiation. The luminescence process of the phosphor is shown in **Figure 5(a)**.

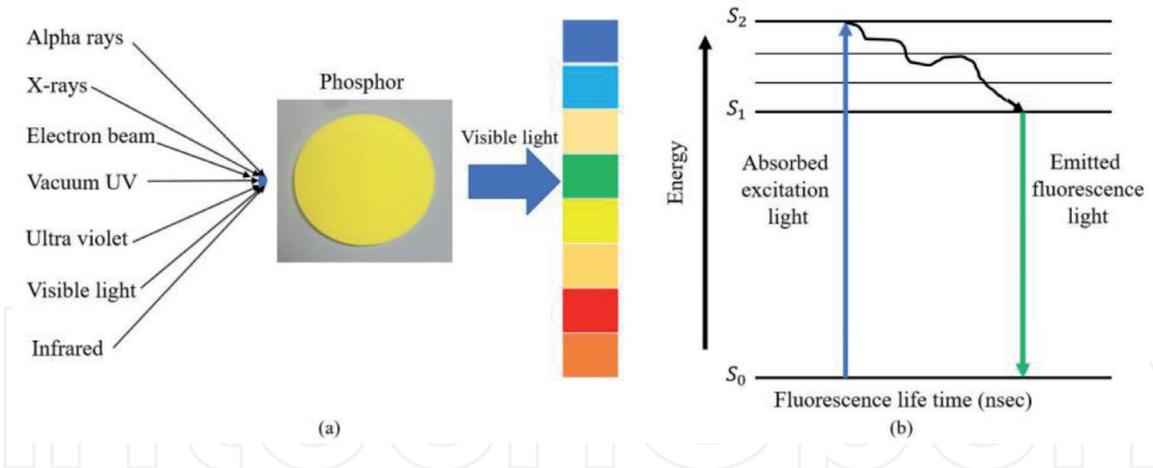


Figure 5.
(a) The luminescence process of phosphor. (b) Jablonski diagram of downconversion luminescence process.

The luminescence process occurs when the activator absorbs the radiant energy and goes to a higher energy state. As the excited state is unstable, the excited photon emits absorbed energy in the relaxation state and falls back to a lower energy state. The Jablonski diagram of the downconversion phosphor luminescence process is shown in **Figure 5(b)**.

The properties associated with ideal phosphor are color quality, CRI, thermal stability, emission spectrum, photoluminescent lifetime, etc. Recent studies have highlighted that phosphor-based white light quality depends on photoluminescent material, size, composition, and arrangement with the package. The absorption rate depends on the crystal structure, particle size, and particle size distribution of phosphor. The difference between the spectral position of the peak of absorption and emission spectra is called stock shift, expressed in wavelength. The extent of the stock shift depends on the characteristic of phosphor. During the illumination process, the phosphor cannot absorb all excitation energy; some of the energy is reflected or transmitted. The most absorbed energy will be released in the form of light, and the rest of the energy may be converted into heat; therefore, in this process, emitted energy is always less than the absorbed energy, and thus the wavelength of excitation light is always shorter than that of emitted light. The phosphor's efficiency depends on how much relaxation (loss of energy) occurs during activation and emission.

Phosphors are increasingly utilized in lighting devices, such as compact fluorescent lamps, LEDs, and LDs. Nowadays, phosphors are using everywhere and extensive research have been carried out to find proper color conversion phosphors. The color conversion phosphor that can be excited by the blue or ultraviolet laser diode is shown in the **Table 2**.

5.1 Properties of some currently available color conversion phosphor

Blue LD-based white light can be generated by using down-conversion phosphors. In this study, two phosphor types were studied as a potential replacement for blue LD-based high CRI lighting and high-speed VLC. These include cesium lead bromide quantum dot (CsPbBr_3 -QD) and potassium fluorosilicate (KSF). We fabricated a polymethyl methacrylate (PMMA) doped phosphor film consisting of CsPbBr_3 -QD and KSF as a color converter. Additionally, we systematically studied the properties of generated white light from the fabricated composite phosphor film and commercially available phosphor coated on glass CL827-R45-XT. The basic introduction of these phosphors is presented below.

Emission color	Phosphor	Excitation wavelength(nm)	Ref.
	SrS : Eu ⁺²	450	[20]
	K ₂ SiF ₆ : Mn ⁴⁺	445	[21]
Red	La ₂ O ₂ S : Eu ⁺²	380–420	[22]
	Gd ₂ O ₂ S : Eu ⁺³	380	[20]
	CaAlSiN ₃ : Eu ⁺²	450–480	[22]
	SrGa ₈ S ₄ : Eu ⁺²	460	[20]
	SrAl ₂ O ₄ : Eu ⁺²	400	[20]
Green	CaSc ₂ O ₄ : Ce ⁺²	450–480	[22]
	CsPbBr ₃	445	[23]
	Ba ₃ Si ₆ O ₁₂ N ₂ : Eu ⁺²	380–420	[22]
	Zns : Ag ⁺	400	[20]
	(Ba,Sr)MgAl ₁₀ O ₁₇ : Eu ⁺²	380–420	[22]
Blue	(Sr,Ba) ₃ MgSi ₂ O ₈ : Eu ⁺²	380–420	[22]
	CsPbCl ₃	385	[23]
	Sr ₃ (PO ₄) ₃ CL : Eu ⁺²	375–400	[24]

Table 2.

Color conversion phosphor that can be excited by the blue or ultraviolet laser diode.

5.2 Cesium lead bromide quantum dot (CsPbBr₃ -QD)

Quantum dots (QDs) are semiconductor nanoparticles, which can be used to generate high-quality solid-state lighting. QDs are separated into three types: cadmium(Cd)-based QDs, Cd-free QDs, and perovskite QDs. Perovskite quantum dots have shown great potential in nanotechnology and optoelectronic applications. They have been widely studied for successful next-generation optoelectronic applications because of their high PLQY and short PL lifetime [25]. The general chemical formula of perovskite quantum dot is APbX₃, where A could be an organic cation such as methylammonium (CH₃NH₃⁺, MA) or inorganic cation such as cesium (Cs⁺) and rubidium (Rb⁺), Pb represents the lead, and X represents different halide, such as Chloride (Cl), bromide (Br), or iodide (I). Inorganic lead halide perovskites have been attracted enormous scientific attention because of their outstanding optoelectronic properties. They have tunable emission wavelength, high quantum yield, fast radiative response, and a short PL lifetime. These characteristics make them highly attractive for wide range next-generation optoelectronic applications such as LED [26, 27], LD [28, 29], solar cells [30], photodetector [31], and wide gamut display [32]. The cubic crystal structure and photoluminescence emission spectra of APbX₃ are shown in **Figure 6(a)** and **(b)**, respectively.

The PL decay lifetime of CsPbBr₃ -QD is approximately 7.0 ± 0.3 ns, as shown in **Figure 7(a)**. The absorption and emission spectra of CsPbBr₃ -QD is shown in **Figure 7(b)**. CsPbBr₃ -QD exhibits an emission peak at 510 nm with narrow full width at half-maximum (FWHM) of 22 nm. CsPbBr₃ -QD exhibits high (PLQY>70%), narrow full width half maximum (FWHM = 22 nm) [34, 36–39], relatively short PL lifetime (7 ns) [32], and a modulation bandwidth of 491 MHz [34],

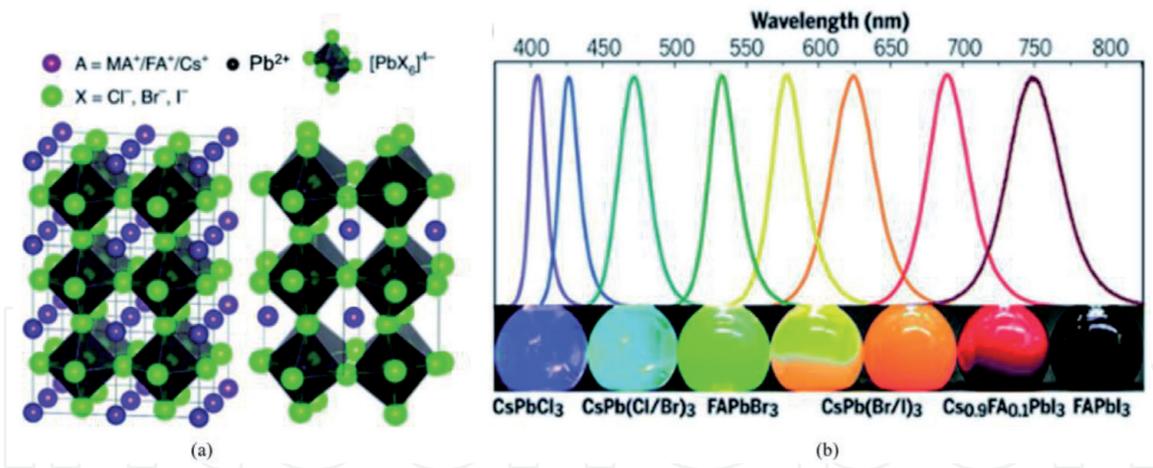


Figure 6.
 (a) The cubic crystal structure of $APbX_3$ [33]. (b) Photoluminescence emission spectra of $APbX_3$ [33].

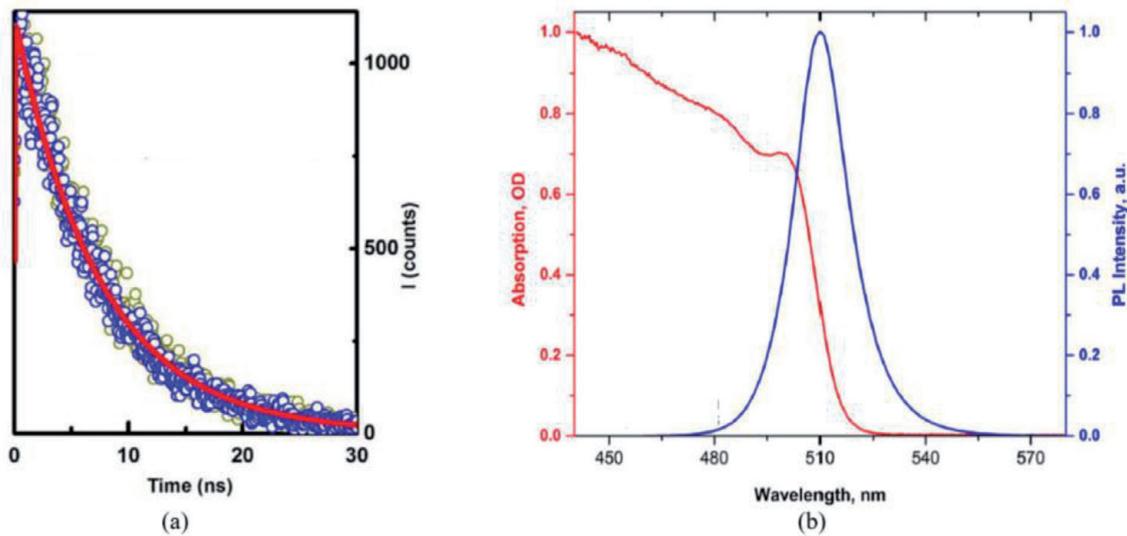


Figure 7.
 (a) Photoluminescence decay of $CsPbBr_3$ -QD monitored at 515 nm [34]. (b) The absorption and emission spectra of $CsPbBr_3$ -QD [35].

which is significantly greater than those of organic materials (40–200 MHz). Therefore, $CsPbBr_3$ -QD is considered a promising substitute for VLC and SSL.

5.3 Potassium fluorosilicate (KSF)

Red emitting phosphor is required to compensate for red color deficiency, which increases phosphor-converted SSL performance, such as high CRI and tunable color temperatures. Nowadays, mostly rare-earth-doped nitride red phosphors are used to generate SSL. Red nitride phosphors have some drawbacks, such as high-temperature synthesis process (1500–2000°C), oxygen-free environment [40, 41], broader emission band (FWHM >75–100 nm) [41, 42], low quantum efficiency [41], and emission peak greater than 650 nm (beyond the sensitivity range of human eyes) [43–45]. Therefore, it was necessary to find an alternative narrow-band red-emitting phosphor to enhance the color qualities further. Efficient narrow-band red-emitting phosphors such as $K_2SiF_6 : Mn^{4+}$ (KSF), with an emission peak at 631 nm, were developed to replace wide band nitride red phosphor. Many studies had been

conducted to optimize the environmental stability, quantum efficiency, and synthesis of KSF [46–48].

Recently, a new class of Mn^{4+} doped fluoride non-rare-earth red phosphor compounds such as $A_2XF_6 : Mn^{4+}$ ($A = Cs, Na, Rb, NH_4, K$; $X = Zr, Ge, Ti, Sn, Si$) has emerged, which has many advantages over red nitride phosphors. Firstly, these components' thermal stability is high and good enough for practical application [49]. Secondly, their internal quantum efficiency is 92–98% [40, 50], and that of nitride red phosphor is 75–80%. Thirdly, they show highly efficient narrow-band red emissions (FWHM <2–10 nm) [51–53], and the red emission peak is generally shorter than 650 nm, which improves color purity and visual colorimetric parameters. The color coordinates of these phosphor components are located deep in the 1931 Commission Internationale de l'Eclairage (CIE) diagram [44]. The excitation and emission spectrum of KSF are shown in **Figure 8**.

The photography of KSF phosphor coated on a glass substrate is shown in **Figure 9(a)**. The acquired emission spectra of generated red light with 445-nm

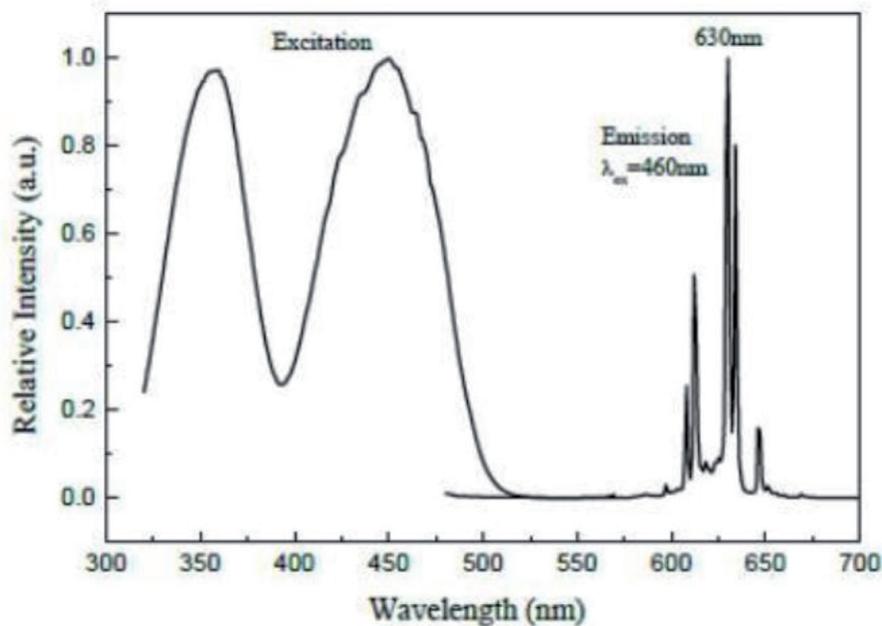


Figure 8.
The excitation and emission spectrum of KSF red phosphor [54].

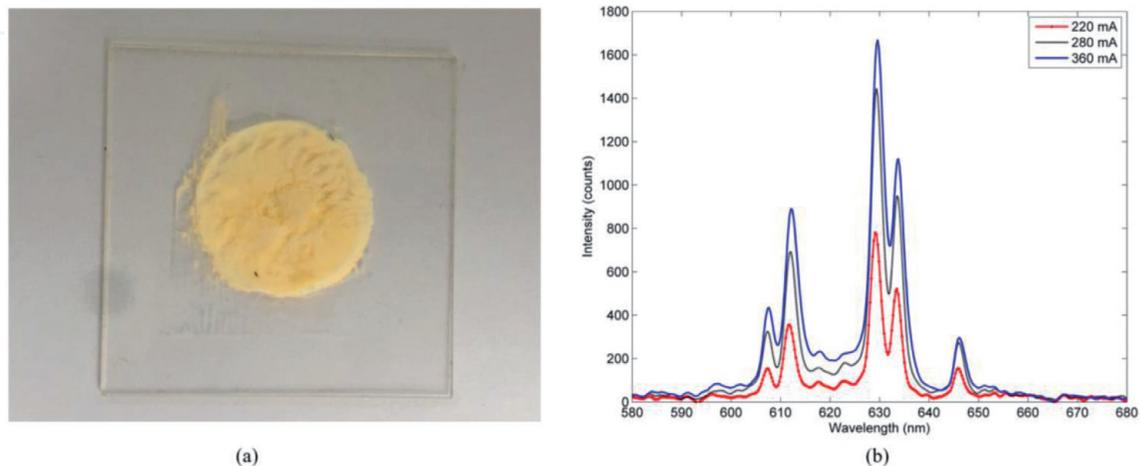


Figure 9.
(a) Photography of KSF phosphor coated on glass. (b) Emission spectra of KSF as functions of driving bias currents.

excitation at room temperature under bias currents of 280 mA, 320 mA, and 360 mA are shown in **Figure 9(b)**. The emission peak of KSF is at 631 nm.

5.4 CL-827-R45-XT

Conventionally, phosphors are mixed with organic or silicone resin to form a phosphor film; however, such composition will ultimately harden and leads to discoloration. Moreover, these components are sensitive to heat and water, reducing the device's lifespan and making them unsuitable for outdoor applications. Phosphor on glass is increasingly replacing conventional color convertors, especially for outdoor high power and high brightness applications. The fabrication process of phosphor on glass is simple as the mixture of phosphors is coated on a transparent glass and can be sintered at 800^o C. The characteristic of generated white light can also be easily controlled by changing the phosphor concentration ratio and thickness. This section studied the properties of generated white light from commercially available phosphor coated on glass CL-827-R45-XT. The Photography of CL-827-R45-XT is shown in **Figure 10**.

The experimental setup to measure emission spectra of generated white light at different bias currents is shown in **Figure 11(a)**. The emission spectra of the generated white light after the blue LD exciting the phosphor coated on glass at room temperature, under bias currents of 220 mA, 240 mA, 280 mA, 320 mA, 360 mA, are shown in **Figure 11(b)**. The peak emission wavelength of blue light is at 439 nm, while that of the yellow light is at 577 nm. It can be seen that the peak emission wavelength of generated light is not changed considerably with increasing

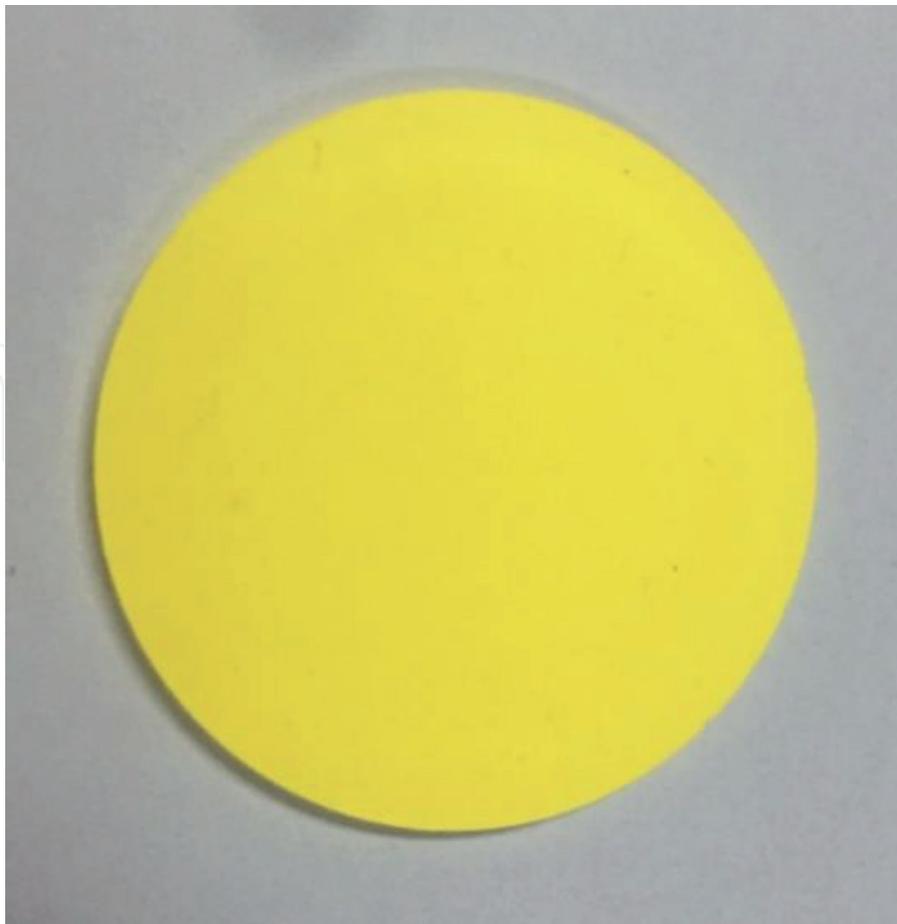


Figure 10.
Photography of CL-827-R45-XT.

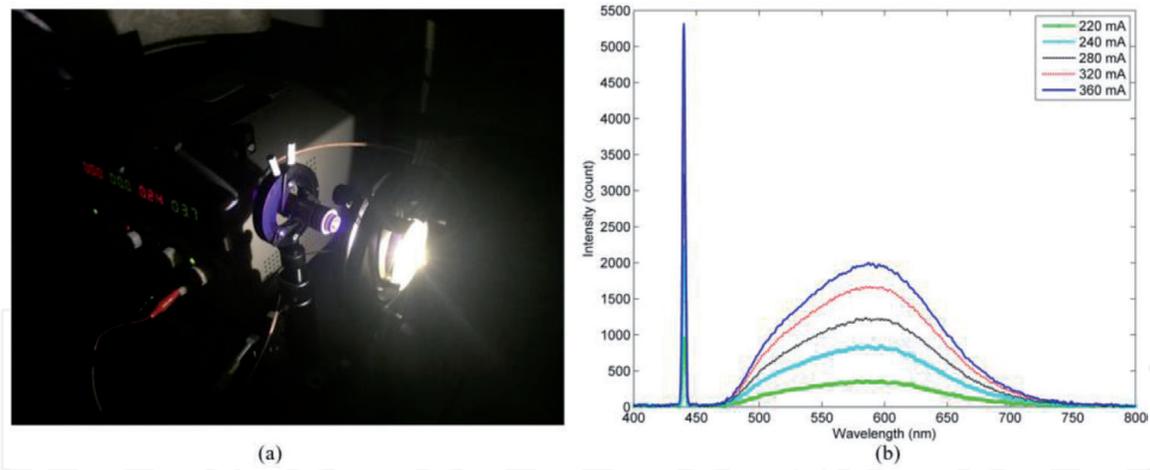


Figure 11. (a) Experimental setup to measure emission spectra. (b) The emission spectra of the generated light at different bias currents.

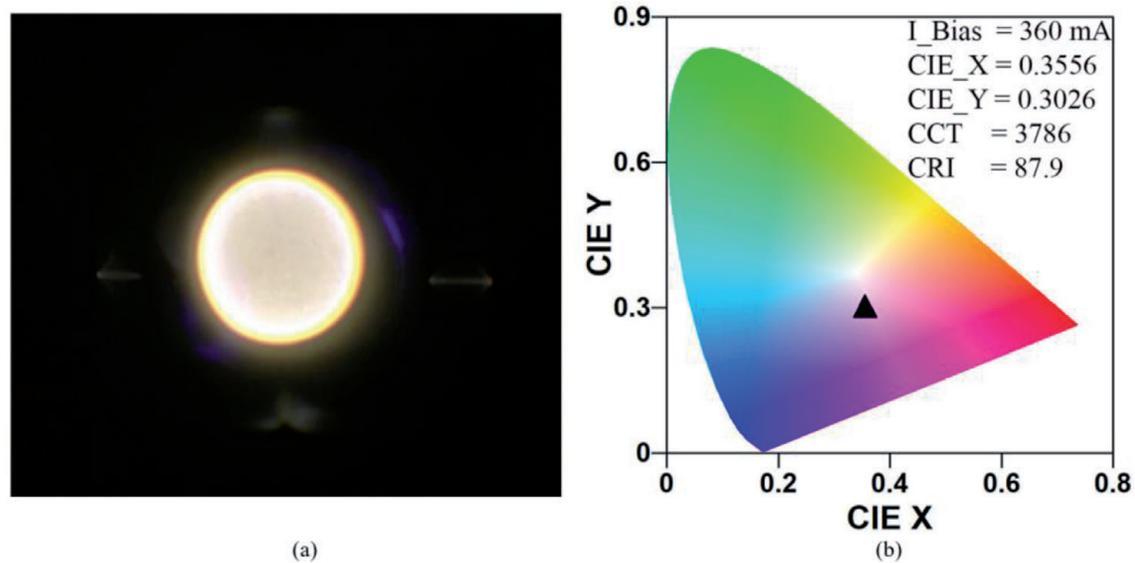


Figure 12 (a) The photography of generated white light spot. (b) Chromaticity coordinates diagram of the generated white light at 360 mA.

bias current, which indicates that the phosphor-coated on glass is suitable to be used with the high injection bias current.

The photography of the generated white light spot is shown in **Figure 12(a)**. The CIE coordinate of the white light source at 360 mA on the CIE 1931 chromaticity diagram is shown in **Figure 12(b)**. At 360 mA, white light has a CCT of 3786, CRI of 87.9, and the CIE coordinates fall at (0.3556, 0.3026), which is very close to the standard neutral white light (0.33, 0.33).

6. High CRI lighting and high-speed visible light communication

The laser based white-light has demonstrated with a color rendering index (CRI) of 78, color temperature of 6000–7000 K, and luminous flux up to 600 lm for a single-chip device [55]. The frequency response of the system adhering phosphor film, is shown in **Figure 13(a)**. The throughput modulation response was reduced mainly due to the relevant absorption and scattering by the phosphorous film. The -10 dB bandwidth of the system is approximately 1500 MHz, at the driving current of 750 mA.

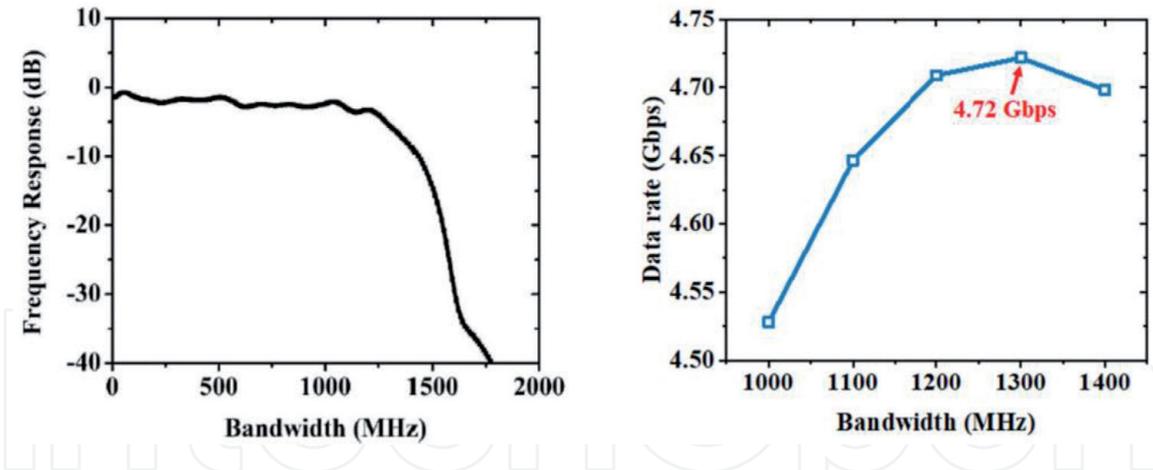


Figure 13. (a) Frequency response of LD laser VLC system. (b) Measured data rate at different bandwidths in the LD laser VLC system [54].

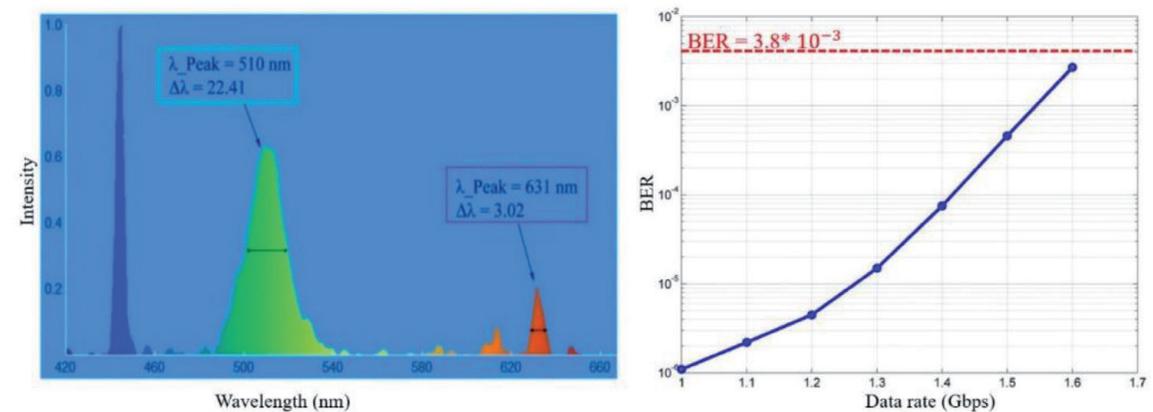


Figure 14. (a) Spectrum of generated white light (b) measured bit-error rates at different data rates.

The data rate achievable at different signal bandwidths is shown in **Figure 13(b)**. It indicates that the white laser VLC system is capable of a high data rate up to 4.72 Gbps at 1300 MHz. At higher signal bandwidths beyond 1400 MHz, the data rate of the VLC system will not steadily increase due to the system's power limitation.

We demonstrated a color-rendering index (CRI) of 93.8, a correlated color temperature (CCT) of 4435 K, and a data rate of 1.6 Gbps under NRZ-OOK modulation by an exciting blue laser diode polymethyl methacrylate (PMMA) doped phosphor film based on cesium lead bromide quantum dot (CsPbBr₃-QD) and potassium fluorosilicate K₂SiF₆:Mn⁴⁺ (KSF) [56]. **Figure 14(a)** shows the optical spectrum of generated white light in which blue, red, and green fluorescent components are observed. In terms of peak emission, the blue light is at 445 nm, the green light is at 510 nm with an FWHM of 22.42 nm, and the red light is at 631 nm with an FWHM of 3.02 nm. Unlike traditional phosphorous materials, CsPbBr₃-QD and KSF have a relatively narrow FWHM. The BER at different data rates is shown in **Figure 14(b)**, where the BER of 2.7 × 10⁻³ is measured at 1.6 Gbps. The obtained BER measurement adheres to the standard FEC threshold of ≤ 3.8 × 10⁻³.

7. Recent progress in blue laser diode-based VLC and SSL

Over the past few years, LD based VLC and SSL techniques have gained significant attention from researchers, due to their advantages, e.g., environmental

Ref	Source	Color converter	CRI	CCT (K)	Modulation scheme	Data rate (Gbps)	Dist (cm)	Year
[57]	B-LD	YAG:Ce	58	4740	OOK	2	5	2015
[3]	B-LD	YAG:Ce	—	6409	16 QAM	4	50	2015
[34]	B-LD	Perovskite	89	3223	OOK	2	—	2016
[58]	B-SLD	YAG:Ce	85.1	3392	OOK	1.45	25	2018
[59]	B-SLD	Y-phosphor	88.2	—	16-QAM	3.4	100	2019
[60]	B-LD	YAG:Ce	67.2	6391	OOK	1	—	2019
[61]	B-LD	Y-phosphor	—	—	OOK	1.25	100	2019
[62]	B-SLD	Perovskite	91	6113	—	—	—	2019
[56]	B-LD	CsPbBr ₃ /KSF	93.8	4435	OOK	1.6	50	2020
[63]	B-LD	YAG:Ce	—	—	OFDM	6.915	150	2020
[64]	2- B-LD	Y-phosphor	—	—	OFDM	22.45	300	2020
[65]	B-LD	CsPbBr ₃ /KSF	91	5056	OOK	1.4	30	2020

B-LD, SLD stand for blue laser diode and superluminescent diode, respectively. YAG: Ce, CsPbBr₃, KSF stand for yttrium aluminum garnet cerium-doped, cesium lead bromide and potassium fluorosilicate, respectively. OOK, QAM, OFDM denote for on-off keying, quadrature amplitude modulation, orthogonal frequency division multiplexing, respectively.

Table 3.

Recent progress in blue laser-based VLC and SSL using phosphors.

friendliness, minimum light-emitting surface, ultrafast operating speed, high efficiency, long lifetime and small footprint. By leveraging the advantages mentioned above, LD-based VLC and SSL is outperforming LED-based VLC and SSL. This technique promises wide applications in academia, science, and industry. Meanwhile, many research laboratories around the world have been focusing on blue laser-based VLC and SSL. The recent research achievements in blue laser-based VLC and SSL is summarized in **Table 3**.

8. Summary

Nowadays white light based on blue laser diode has become the rapidly growing technology for high speed VLC and high CRI lighting. This Chapter aims to understand the blue laser diode-based VLC and SSL using color converter remote phosphor to overcome the bottlenecks of LED-based VLC and SSL. Recently, phosphors are using everywhere; therefore, multiple approaches and research have been carried out to find the best color conversion phosphor. We have studied the down-conversion luminescence properties of cesium lead bromide quantum dot (CsPbBr₃-QD) and Potassium silicon fluoride K₂SiF₆:Mn⁴⁺ (KSF). Furthermore, we have studied the properties of generated white light from commercially available phosphor coated on glass CL-827-R45-XT by changing bias currents. We demonstrated a VLC and SSL system simultaneously with a data rate of 1.6 Gbps over 50 cm free-space link based on NRZ-OOK modulation. Additionally, the generated white light exhibits with low CCT of 4435 K and CRI of 93.8. According to our discussions, we can conclude that laser diode based generated white light can be used for both high-speed visible light communication and solid-state lighting simultaneously.

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References

- [1] Kim, J. S., Jeon, P. E., Park, Y. H., Choi, J. C., Park, H. L., Kim, G. C., & Kim, T. W. (2004). White-light generation through ultraviolet-emitting diode and white-emitting phosphor. *Applied Physics Letters*, 85(17), 3696-3698. DOI: 10.1063/1.1808501
- [2] Elayan, H., Amin, O., Shihada, B., Shubair, R. M., & Alouini, M. S. (2019). Terahertz band: The last piece of RF spectrum puzzle for communication systems. *IEEE Open Journal of the Communications Society*, 1, 1-32. DOI:10.1109/OJCOMS.2019.2953633
- [3] Retamal, J. R. D., Oubei, H. M., Janjua, B., Chi, Y. C., Wang, H. Y., Tsai, C. T., ... & Ooi, B. S. (2015). 4-Gbit/s visible light communication link based on 16-QAM OFDM transmission over remote phosphor-film converted white light by using blue laser diode. *Optics express*, 23(26), 33656-33666. DOI:10.1364/OE.23.033656
- [4] Rahman, A. B. M., Li, T., & Wang, Y. (2020). Recent Advances in Indoor Localization via Visible Lights: A Survey. *Sensors*, 20(5), 1382. DOI:10.3390/s20051382
- [5] Kim, Y. H., Cahyadi, W. A., & Chung, Y. H. (2015). Experimental demonstration of VLC-based vehicle-to-vehicle communications under fog conditions. *IEEE Photonics Journal*, 7(6), 1-9. DOI:10.1109/JPHOT.2015.2499542
- [6] Mousa, F. I., Almaadeed, N., Busawon, K., Bouridane, A., Binns, R., & Elliott, I. (2018). Indoor visible light communication localization system utilizing received signal strength indication technique and trilateration method. *Optical Engineering*, 57(1), 016107. DOI:10.1117/1.OE.57.1.016107
- [7] Xu, Jing, et al. "Underwater laser communication using an OFDM-modulated 520-nm laser diode." *IEEE Photonics Technology Letters* 28.20 (2016): 2133-2136. DOI:10.1109/LPT.2016.2582542
- [8] Liu, X., Yi, S., Zhou, X., Zhang, S., Fang, Z., Qiu, Z. J., ... & Tian, P. (2018). Laser-based white-light source for high-speed underwater wireless optical communication and high-efficiency underwater solid-state lighting. *Optics express*, 26(15), 19259-19274. DOI:10.1364/OE.26.019259
- [9] Alimi, I., Shahpari, A., Sousa, A., Ferreira, R., Monteiro, P., & Teixeira, A. (2017). Challenges and opportunities of optical wireless communication technologies. *Optical communication technology*, 10 DOI:10.5772/intechopen.69113
- [10] https://science.osti.gov/media/bes/pdf/reports/files/Basic_Research_Needs_for_Solid-State_Lighting_rpt.pdf
- [11] www.ulooptics.com/wp-content/uploads/Neptune-data-table.jpg
- [12] Xu, Y., Chen, L., Li, Y., Song, G., Wang, Y., Zhuang, W., & Long, Z. (2008). Phosphor-conversion white light using InGaN ultraviolet laser diode. *Applied Physics Letters*, 92(2), 021129. DOI:10.1063/1.2835703
- [13] Xu, Y., Hu, H., Zhuang, W., Song, G., Li, Y., & Chen, L. (2009). White light emission from ultraviolet laser diode. *Laser physics*, 19(3), 403-406. DOI:10.1134/S1054660X09030086
- [14] Ryu, H. Y., & Kim, D. H. (2010). High-brightness phosphor-conversion white light source using InGaN blue laser diode. *Journal of the Optical Society of Korea*, 14(4), 415-419. DOI:10.3807/JOSK.2010.14.4.415
- [15] Denault, K. A., Cantore, M., Nakamura, S., DenBaars, S. P., &

- Seshadri, R. (2013). Efficient and stable laser-driven white lighting. *Aip Advances*, 3(7), 072107. DOI:10.1063/1.4813837
- [16] Wierer Jr, J. J., & Tsao, J. Y. (2015). Advantages of III-nitride laser diodes in solid-state lighting. *physica status solidi (a)*, 212(5), 980-985. DOI: 10.1002/pssa.201431700
- [17] Wanka, J., 2017, "Photonics in Germany," Munich, Germany, Germany, accessed Aug. 5, 2019, <https://agustos.com/wp-content/uploads/2018/07/BMW-Article-Photonics-in-Germany-2017.pdf>
- [18] Max, 2017, "Laser headlight in automotive lighting," Audi, Ingolstadt, Germany, accessed Aug. 5, 2019, http://www.serafim-tech.com/blog/laser-headlight-in-automotive-lighting.html?tdsourcetag=s_pcqq_aiomsg
- [19] Ma, Y., & Luo, X. (2020). Packaging for laser-based white lighting: status and perspectives. *Journal of Electronic Packaging*, 142(1). DOI:10.1115/1.4044359
- [20] Rossner, W. (2003) Trivalent rare earth activated phosphors for wavelength conversion in LEDs: Possibilities and limitations, Phosphor Global Summit, Scottsdale, AR, USA, Conference Paper 14, pp. 1-18.
- [21] Osborne, R. A., Cherepy, N. J., Seeley, Z. M., Payne, S. A., Drobshoff, A. D., Srivastava, A. M., ... & Schlagel, D. L. (2020). New red phosphor ceramic K₂SiF₆: Mn⁴⁺. *Optical Materials*, 107, 110140. DOI:10.1016/j.optmat.2020.110140
- [22] Lin, C. C., & Liu, R. S. (2011). *Advances in phosphors for light-emitting diodes*. The journal of physical chemistry letters, 2(11), 1268-1277. DOI:10.1021/jz2002452
- [23] <https://quantum-solutions.com/product/perovskite-quantum-dots/>
- [24] Radkov, E. (2003) White light with UV LEDs, Phosphor Global Summit, Scottsdale, AR, USA, Conference Paper 20, pp. 1-19. DOI:10.1117/12.512865
- [25] Huang, H., Bodnarchuk, M. I., Kershaw, S. V., Kovalenko, M. V., & Rogach, A. L. "Lead halide perovskite nanocrystals in the research spotlight: Stability and defect tolerance." *ACS energy letters* 2.9 (2017): 2071-2083. DOI:10.1021/acsenenergylett.7b00547
- [26] Song, J., Li, J., Li, X., Xu, L., Dong, Y., & Zeng, H. (2015). Quantum dot light-emitting diodes based on inorganic perovskite cesium lead halides (CsPbX₃). *Advanced materials*, 27(44), 7162-7167. DOI:10.1002/adma.201502567
- [27] Davis, N. J., de la Peña, F. J., Tabachnyk, M., Richter, J. M., Lamboll, R. D., Booker, E. P., ... & Greenham, N. C. (2017). Photon reabsorption in mixed CsPbCl₃: CsPbI₃ perovskite nanocrystal films for light-emitting diodes. *The Journal of Physical Chemistry C*, 121(7), 3790-3796. DOI:0.1021/acs.jpcc.6b12828
- [28] Fu, Y., Zhu, H., Stoumpos, C. C., Ding, Q., Wang, J., Kanatzidis, M. G., ... & Jin, S. (2016). Broad wavelength tunable robust lasing from single-crystal nanowires of cesium lead halide perovskites (CsPbX₃, X= Cl, Br, I). *ACS nano*, 10(8), 7963-7972. DOI:10.1021/acsnano.6b03916
- [29] Yan, D., Shi, T., Zang, Z., Zhou, T., Liu, Z., Zhang, Z., ... & Tang, X. (2019). Ultrastable CsPbBr₃ perovskite quantum dot and their enhanced amplified spontaneous emission by surface ligand modification. *Small*, 15(23), 1901173. DOI:10.1002/sml.201901173
- [30] Jeon, N. J., Noh, J. H., Yang, W. S., Kim, Y. C., Ryu, S., Seo, J., & Seok, S. I. (2015). Compositional engineering of perovskite materials for high-performance solar cells. *Nature*, 517(7535), 476-480. DOI:10.1038/nature14133

- [31] Ramasamy, P., Lim, D. H., Kim, B., Lee, S. H., Lee, M. S., & Lee, J. S. (2016). All-inorganic cesium lead halide perovskite nanocrystals for photodetector applications. *Chemical communications*, 52(10), 2067-2070. DOI:10.1039/C5CC08643D
- [32] Protesescu, L., Yakunin, S., Bodnarchuk, M. I., Krieg, F., Caputo, R., Hendon, C. H., ... & Kovalenko, M. V. (2015). Nanocrystals of cesium lead halide perovskites (CsPbX₃, X= Cl, Br, and I): novel optoelectronic materials showing bright emission with wide color gamut. *Nano letters*, 15(6), 3692-3696. DOI:10.1021/nl5048779
- [33] Chen, Y., & Zhao, Y. (2020). Incorporating quantum dots for high efficiency and stable perovskite photovoltaics. *Journal of Materials Chemistry A*, 8(47), 25017-25027. DOI:10.1039/D0TA09096D
- [34] Dursun, I., Shen, C., Parida, M. R., Pan, J., Sarmah, S. P., Priante, D., ... & Bakr, O. M. (2016). Perovskite nanocrystals as a color converter for visible light communication. *Acs Photonics*, 3(7), 1150-1156. DOI: 10.1021/acsp Photonics.6b00187
- [35] https://quantum-solutions.com/wp-content/uploads/Handout_Perovskite-QDs.pdf
- [36] Lou, S., Xuan, T., & Wang, J. (2019). Stability: A desiderated problem for the lead halide perovskites. *Optical Materials: X*, 1, 100023. DOI:10.1016/j.omx.2019.100023
- [37] Yang, D., Cao, M., Zhong, Q., Li, P., Zhang, X., & Zhang, Q. (2019). All-inorganic cesium lead halide perovskite nanocrystals: synthesis, surface engineering and applications. *Journal of Materials Chemistry C*, 7(4), 757-789. DOI:10.1039/C8TC04381G
- [38] Hu, F., Zhang, H., Sun, C., Yin, C., Lv, B., Zhang, C., ... & Xiao, M. (2015). Single photon emission from single perovskite nanocrystals of cesium lead bromide. arXiv preprint arXiv:1509.02666. DOI: 10.1021/acsnano.5b05769
- [39] Han, Q., Wu, W., Liu, W., & Yang, Y. (2017). The peak shift and evolution of upconversion luminescence from CsPbBr₃ nanocrystals under femtosecond laser excitation. *RSC advances*, 7(57), 35757-35764. DOI:10.1039/C7RA06211G
- [40] Hou, Z., Tang, X., Luo, X., Zhou, T., Zhang, L., & Xie, R. J. (2018). A green synthetic route to the highly efficient K₂SiF₆:Mn⁴⁺ narrow-band red phosphor for warm white light-emitting diodes. *Journal of Materials Chemistry C*, 6(11), 2741-2746. DOI:10.1039/C8TC00133B
- [41] Chen, Y., Wang, M., Wang, J., Wu, M., & Wang, C. (2014). A high color purity red emitting phosphor CaYAlO₄:Mn⁴⁺ for LEDs. *Journal of Solid-State Lighting*, 1(1), 1-8. DOI:10.1186/s40539-014-0015-4
- [42] Piao, X., Machida, K. I., Horikawa, T., Hanzawa, H., Shimomura, Y., & Kijima, N. (2007). Preparation of CaAlSiN₃:Eu²⁺ phosphors by the self-propagating high-temperature synthesis and their luminescent properties. *Chemistry of Materials*, 19(18), 4592-4599. DOI:10.1021/cm070623c
- [43] Wang, L. Y., Song, E. H., Zhou, Y. Y., Deng, T. T., Ye, S., & Zhang, Q. Y. (2017). Synthesis and warm-white LED applications of an efficient narrow-band red emitting phosphor, Rb₂ZrF₆:Mn⁴⁺. *Journal of Materials Chemistry C*, 5(29), 7253-7261. DOI:10.1039/C7TC02196H
- [44] Zhao, C., Cao, S. X., Hu, K., Li, S., & Wang, M. (2020). An in-situ synthesized multiphase phosphor MgO_{6-x}Al₂Si_{1-8O7-2}:xEu²⁺ with a broad emission spectrum and thermal

anti-quenching property. *Ceramics International*. DOI: 10.1016/j.ceramint.2020.01.022

[45] Nersisyan, Hayk, Hyung Il Won, and Chang Whan Won. "Highly effective synthesis and photoluminescence of Sr₂Si₅N₈:Eu²⁺ red-emitting phosphor for LEDs." *Chemical Communications* 47.43 (2011): 11897-11899. DOI: 10.1039/C1CC15427C

[46] Sijbom, H. F., Verstraete, R., Joos, J. J., Poelman, D., & Smet, P. F. (2017). K₂SiF₆:Mn⁴⁺ as a red phosphor for displays and warm-white LEDs: a review of properties and perspectives. *Optical Materials Express*, 7(9), 3332-3365. DOI: 10.1364/OME.7.003332

[47] Huang, L., Liu, Y., Yu, J., Zhu, Y., Pan, F., Xuan, T., ... & Wang, J. (2018). Highly stable K₂SiF₆:Mn⁴⁺@K₂SiF₆ composite phosphor with narrow red emission for white LEDs. *ACS applied materials & interfaces*, 10(21), 18082-18092. DOI: 10.1021/acsami.8b03893

[48] Lee, M. J., Song, Y. H., Song, Y. L., Han, G. S., Jung, H. S., & Yoon, D. H. (2015). Enhanced luminous efficiency of deep red emitting K₂SiF₆:Mn⁴⁺ phosphor dependent on KF ratio for warm-white LED. *Materials Letters*, 141, 27-30. DOI: 10.1016/j.matlet.2014.11.025

[49] Wang, L., Wang, X., Kohsei, T., Yoshimura, K. I., Izumi, M., Hirotsuki, N., & Xie, R. J. (2015). Highly efficient narrow-band green and red phosphors enabling wider color-gamut LED backlight for more brilliant displays. *Optics express*, 23(22), 28707-28717. DOI: 10.1364/OE.23.028707

[50] Zhu, H., Lin, C. C., Luo, W., Shu, S., Liu, Z., Liu, Y., ... & Chen, X. (2014). Highly efficient non-rare-earth red emitting phosphor for warm white light-emitting diodes. *Nature communications*, 5(1), 1-10. DOI: 10.1038/ncomms5312

[51] Oh, J. H., Kang, H., Ko, M., & Do, Y. R. (2015). Analysis of wide color gamut of green/red bilayered freestanding phosphor film-capped white LEDs for LCD backlight. *Optics express*, 23(15), A791-A804. DOI: 10.1364/OE.23.00A791

[52] Liao, C., Cao, R., Ma, Z., Li, Y., Dong, G., Sharafudeen, K. N., & Qiu, J. (2013). Synthesis of K₂SiF₆:Mn⁴⁺ Phosphor from SiO₂ Powders via Redox Reaction in HF/KMnO₄ Solution and Their Application in Warm-White LED. *Journal of the American Ceramic Society*, 96(11), 3552-3556. DOI: 10.1111/jace.12533

[53] Zhang, X., Tsai, Y. T., Wu, S. M., Lin, Y. C., Lee, J. F., Sheu, H. S., ... & Liu, R. S. (2016). Facile atmospheric pressure synthesis of high thermal stability and narrow-band red-emitting SrLiAl₃N₄:Eu²⁺ phosphor for high color rendering index white light-emitting diodes. *ACS Applied Materials & Interfaces*, 8(30), 19612-19617. DOI: 10.1021/acsami.6b05485

[54] Tuyet, D. T., Quan, V. T. H., Bondzior, B., Dereń, P. J., Velpula, R. T., Nguyen, H. P. T., ... & Nguyen, H. D. (2020). Deep red fluoride dots-in-nanoparticles for high color quality micro white light-emitting diodes. *Optics Express*, 28(18), 26189-26199. DOI: 10.1364/OE.400848

[55] Shen, Chao, Chicheng Ma, Dong Li, Junhui Hu, Guoqiang Li, Peng Zou, Junwen Zhang, Ziwei Li, and Nan Chi. "High-speed visible laser light communication: devices, systems and applications." In *Broadband Access Communication Technologies XV*, vol. 11711, p. 1171109. International Society for Optics and Photonics, 2021. DOI: 10.1117/12.2578213

[56] Ali, Amjad, Riffat Tehseen, K. M. Mithilesh, Chao Zhang, S. A. Hassnain, Xiao Chen, Xingqi Yang et al. "Blue-laser-diode-based high CRI lighting and high-speed visible light communication

using narrowband green–/red-emitting composite phosphor film.” *Applied optics* 59, no. 17 (2020): 5197-5204. DOI: 10.1364/AO.392340

[57] Lee, Changmin, Chao Shen, Hassan M. Oubei, Michael Cantore, Bilal Janjua, Tien Khee Ng, Robert M. Farrell et al. “2 Gbit/s data transmission from an unfiltered laser-based phosphor-converted white lighting communication system.” *Optics express* 23, no. 23 (2015): 29779-29787. DOI: 10.1364/OE.23.029779

[58] Alatawi, Abdullah A., Jorge A. Holguin-Lerma, Chun Hong Kang, Chao Shen, Ram Chandra Subedi, Abdulrahman M. Albadri, Ahmed Y. Alyamani, Tien Khee Ng, and Boon S. Ooi. “High-power blue superluminescent diode for high CRI lighting and high-speed visible light communication.” *Optics Express* 26, no. 20 (2018): 26355-26364. DOI: 10.1364/OE.26.026355

[59] Shen, Chao, Jorge A. Holguin-Lerma, Abdullah A. Alatawi, Peng Zou, Nan Chi, Tien Khee Ng, and Boon S. Ooi. “Group-III-nitride superluminescent diodes for solid-state lighting and high-speed visible light communications.” *IEEE Journal of Selected Topics in Quantum Electronics* 25, no. 6 (2019): 1-10. DOI: 10.1109/JSTQE.2019.2915995

[60] Ooi, Ee-Ning, Xiaobin Sun, Boon S. Ooi, Tien Khee Ng, and Chao Shen. “Study on laser-based white light sources.” In *Light-Emitting Devices, Materials, and Applications*, vol. 10940, p. 109401G. International Society for Optics and Photonics, 2019. DOI: 10.1117/12.2511094

[61] Yeh, Chien-Hung, Chi-Wai Chow, and Liang-Yu Wei. “1250 Mbit/s OOK wireless white-light VLC transmission based on phosphor laser diode.” *IEEE Photonics journal* 11, no. 3 (2019): 1-5. DOI: 10.1109/JPHOT.2019.2911411

[62] Alatawi, Abdullah A., Jorge A. Holguin-Lerma, Chun Hong Kang, Chao Shen, Ibrahim Dursun, Lutfan Sinatra, Abdulrahman M. Albadri et al. “Blue superluminescent diodes with GHz bandwidth exciting perovskite nanocrystals for high CRI white lighting and high-speed VLC.” In *CLEO: Science and Innovations*, pp. SM3N-4. Optical Society of America, 2019. DOI: 10.1364/CLEO_SI.2019.SM3N.4

[63] Wei, Liang-Yu, Yang Liu, Chi-Wai Chow, Guan-Hong Chen, Ching-Wei Peng, Pin-Cheng Guo, Jui-Feng Tsai, and Chien-Hung Yeh. “6.915-Gbit/s white-light phosphor laser diode-based DCO-OFDM visible light communication (VLC) system with functional transmission distance.” *Electronics Letters* 56, no. 18 (2020): 945-947. DOI:10.1049/el.2020.1379

[64] Lee, Changmin, et al. “Advanced LiFi technology: Laser light.” *Light-Emitting Devices, Materials, and Applications XXIV*. Vol. 11302. International Society for Optics and Photonics, 2020. DOI: 10.1117/12.2537420

[65] Ali, Amjad, K. M. Mithilesh, Riffat Tehseen, Chao Zhang, Zejun Zhang, Syed Raza Mehdi, and Jing Xu. “A novel integrated fully passive optical network for free-space optics and visible light communication for last-mile access network based on composite phosphor film.” In *International Conference on Optoelectronic and Microelectronic Technology and Application*, vol. 11617, p. 1161719. International Society for Optics and Photonics, 2020. doi. org/10.1117/12.2585093