A tutorial on laser-based visible light communications

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Facing escalating demands for high-speed, large-bandwidth, and low-latency wireless data links, laser communication technology has emerged as a promising technology. While free space optical communication conventionally utilizes near-infrared light sources, there has been growing interest in exploring new spectral resources, including visible lasers. Recently, laser-based white light has been demonstrated in visible light communication, with a unique capability to seamlessly integrate with illumination and display systems. This review summarizes the key devices and system technologies in semiconductor-laser-based white light for VLC-related applications. The recent advances and many emerging applications in the evolution of lighting, display, and communication are discussed.

Keywords: visible light communication, LiFi, laser lighting, GaN laser, semiconductor laser

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1. Introduction

The past decade has witnessed unprecedented growth in data capacity and speed. Lightwave-based communication technology is considered to be one of the solutions in the next-generation 6G wireless network. Benefiting from the ubiquitous solid-state lighting infrastructure, visible light communication (VLC) using semiconductor light emitters, such as light emitting diodes (LEDs) and laser diodes (LDs) has emerged as a disruptive technology transcending the boundaries of traditional illumination, display, and optical communication. Recently, white light generation using semiconductor lasers has attracted growing research interests due to many potential advantages, including improved energy efficiency, high power intensity and enhanced color control [1]. Laser-based VLC shows the potential to transform various applications, such as smart traffic, augmented reality (AR), virtual reality (VR), light fidelity (LiFi), indoor positioning, underwater wireless optical communication, and inter-satellite communication. As part of future wireless communication technologies, laser-based VLC will help to achieve a space-air-ground-sea integrated network (Fig. 1), ushering in an era of unparalleled integration and innovation. In this review, the basic concepts, key enabling device technology, developments in sub-system technology, advances in system technology, and novel applications of laser-based VLC will be discussed.

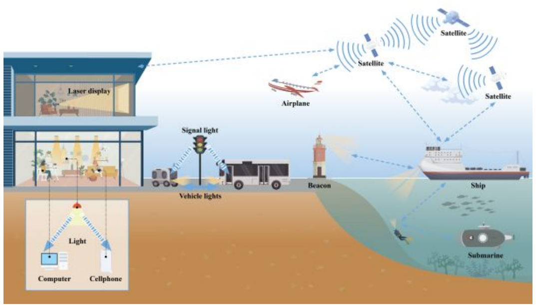

Figure 1. Applications of visible light communication in future networks.

Laser-based lighting. Laser-based lighting is an emerging lighting technology that utilizes lasers as light sources. Gallium nitride (GaN)-based LEDs have been widely used as light sources. However, their optical efficiency tends to decrease at high power densities, limiting their effectiveness as high-brightness light sources. In contrast, LDs do not exhibit an "efficiency droop" and can provide higher optical power density, resulting in superior lighting effects[2]. Additionally, LDs have a smaller divergence angle and higher collimation compared to LEDs, leading to reduced energy loss and longer illumination distances[3]. However, the behavior of lasers can be significantly influenced by temperature. Therefore, effective thermal management techniques, such as improved heat sink devices, are required to ensure optimal lighting performance[4].

Laser-based display. The concept of using lasers for display purposes was proposed as early as the 1960s, but the high cost and large size of solid-state lasers hindered their development[5]. Recent advancements in semiconductor laser technology have resulted in smaller yet more powerful lasers, paving the way for the commercialization of laser-based display technologies. Laser displays offer advantages such as a wide color gamut, high contrast, and enhanced color saturation owing to the coherent emission characteristics of lasers in the visible light range[6]. Light sources for laser displays include diode-pumped solid-state lasers, edge-emitting LDs, vertical-cavity surface-emitting lasers (VCSELs), and optically pumped semiconductor lasers (OPSLs)[7]. Additionally, new types of lasers, such as random laser arrays and circular polarization lasers, have been developed for specific applications such as wearable devices and 3D displays[6],[8].

Optical wireless communication (OWC). Optical wireless communication differs from conventional radio-frequency (RF) wireless communication by utilizing visible, infrared (IR), and ultraviolet (UV) light as signal carriers[9]. OWC communication links, particularly in outdoor environments, offer a higher available bandwidth and significantly higher data rates than RF links. LEDs and LDs are commonly used as transmitters in OWC systems. LDs, in particular, provide higher bandwidth, narrower full width at half maxima (FWHM), and higher directional brightness, making them suitable for long-distance OWC transmission[10]. OWC has a broad range of applications, not only suitable for indoor and short-range communications but also for outdoor and long-distance communications, such as intercity communications and satellite communications. Satellite communication is considered to be a crucial technology for 6G communication. The advantages of lasers make LDs well-suited for satellite communication in addition to terrestrial applications[11].

Light Fidelity (LiFi). LiFi is one of the specific forms of OWC, which was introduced by Harald Haas in 2011[12]. LiFi networks utilize LEDs as signal emitters[13]. LiFi is primarily used for indoor network communication, such as within offices and homes, focusing on local and internal environments for data transmission. The growing data traffic generated by smartphones and other RF communication devices has resulted in a strain on the RF signal spectrum resources[14]. LiFi networks alleviate this spectrum resource shortage by modulating signals in higher frequency bands through light[15]. LiFi offers benefits such as high capacity, enhanced security, and efficient resource utilization of light resources for simultaneous lighting and communication. While LiFi has the potential to replace wireless fidelity (WiFi), it is not mutually exclusive with WiFi technology, as WiFi technology is well established and widely deployed. A combination of LiFi and WiFi that leverages the advantages of both technologies becomes a future perspective[16].

2. Devices

The study of LD started in the 1960s, when Hall et al. put forward the first demonstration of LD[17]. LDs feature high luminous flux, high temporal and spatial coherence, compact size, and low power consumption over LEDs, thus having advantages in projectors, automotive headlamps, and various lighting and display scenarios[18]. The operational wavelength of a semiconductor LD primarily relies on the semiconductor material employed as the active medium. Attaining consistent efficiency levels across a broad operating wavelength range in LDs poses enormous challenges in material epitaxy, device fabrication, and chip-scale integration and packaging. Initially, dominant research attention was directed toward GaAs-based red LDs, resulting in notable progress. Subsequent advancements in GaN-based laser technology have driven progress and accelerated the development of semiconductor lasers in blue and green wavelengths.

With the increasing demands for lighting, display, and communication applications, the requirements for LD devices have become more stringent. In display applications, the utilization of red, green, and blue (RGB) lasers not only enhances the efficiency but also enhances the color reproducing property[19]. Furthermore, RGB LDs serve as fundamental components for laser-based white light lighting and hybrid applications.

In this section, we present the most recent research on the lighting and efficiency performance of LDs at various wavelengths.

Blue Laser Diode. Whether using RGB tri-color light composite or phosphor conversion, the quality of blue lasers plays a crucial role in generating high-quality white light. Among various performance metrics, a high level of energy efficiency under continuous wave (CW) operation stands out as a fundamental requirement for numerous applications. This efficiency is commonly quantified using the wall-plug efficiency (WPE), which is equivalent to the electrical-to-optical power conversion efficiency (PCE). InGaN/GaN blue LEDs achieve an electrical-to-optical power conversion efficiency of over 80%, whereas the reported figures for blue LDs can hardly reach 50%[20]. Piprek et al. conducted theoretical research, and their work illustrated and validated the mechanisms underlying electro-optical energy conversion efficiency through a combination of simulations and experiments. It also offered an analysis of the limitations of various light sources that have reached the peak PCE[21].In recent years, the WPE of blue LD has gradually improved, with a significant 50% milestone achieved over the past two years. Figure 2 shows the growth trend of the blue and green lasers WPE and their future trends.

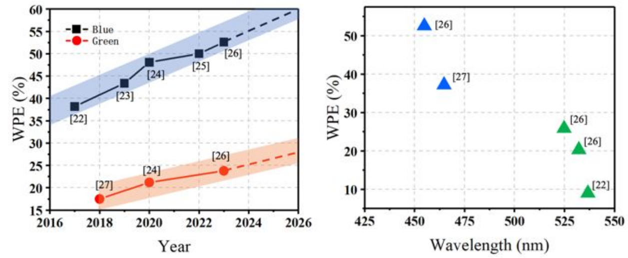

Figure 2. Promotion of Blue and Green LDs' WPE in recent years. The data is from the references [22-27]. Figure 3. WPE varies with wavelength. The data is from the references [22, 26, 27].

GaN-based blue LDs capable of delivering high optical power outputs in the watt class are considered essential, particularly for applications such as laser displays, laser lighting, and underwater communication. Nevertheless, the fabrication of GaN-based blue LDs with high optical power is a challenging endeavor that involves intricate processes in epitaxial growth, device manufacturing, and packaging. An output optical power of over 5 W can be achieved by forming a single ridge blue LD with a 45-μm ridge width[26]. The significant advantages of BLDs for visible light communication lie in their large modulation bandwidth and high transmission rates. In recent work, a c-plane GAN-based BLD was reported to achieve 5.9 GHz (-3 dB) modulation bandwidth, setting the current record for the highest bandwidth among known mini-LDs, contributing to a single-channel speed of 20 Gbps[28].

Green Laser Diode. The development of energy-efficient green laser diodes remains a challenging topic among the visible and near-infrared spectrum range, namely the "green gap"[29]. The peak gain of GaN-based LDs decreases as the emission wavelength shifts from the violet to the green range, leading to an increase in threshold current and a decrease in the efficiency of green LDs[30]. For example, green LDs have reached only approximately half the WPE of blue lasers, making green LD a bottleneck in RGB tri-color white light for display and lighting applications. Figure 2 demonstrates the variation of WPE with wavelength, which can be as high as 25.9% at 525 nm and only 8.8% at 537 nm in the green band.

Recent reports from Nichia, Osram, Chinese Academy of Sciences, University of California Santa Barbara (UCSB) have shown that the optical power and lifetime of green LDs can be improved by engineering the epitaxial and fabrication processes, such as addressing the crystalline defects caused by In-doping [31]. From the 2010s to the 2020s, watt-class green LDs have been realized, and the WPE has been increased to over 20% [23, 24, 27, 32-35]. In 2023, Nichia reported a 20-μm single-ridge green LD at 525 nm, with 1.86-W high power and 23.8% WPE, estimated to have 10000 hour lifetime[26].

Moreover, green light has better penetration through fog, haze, and other atmospheric conditions, and is less prone to interference from ambient light sources, thus having excellent performance in long-distance scenarios. Recent research has conducted a 100-meter transmission at a high data rate of 11.2 Gbps with GLD[36].

Red Laser Diode. Red lasers have been developed since the 1970s and have been used for leveling and ranging as well as optical storage and laser printing. The output power and performance of red LDs have been improving since then. A single-mode red LD at 638 nm can realize 200-mW output power, and the WPE is approximately 33%, which will further increase multi-mode emission under pulsed operation[37]. In the field of communication, red LD can outperform blue and green LD in a tri-color laser-based visible light communication system[38]. Red lasers have the potential for biomedical analytical applications, such as cancer therapy, skincare, as well as quantum technologies[39].

Violet Laser Diode. Violet LD has replaced red light for optical data storage since its discovery[40]. Violet LD also plays a crucial role in white light generation. To achieve a high color rendering index (CRI), light sources based on violet LED or lasers have been developed for high-end lighting applications, such as in museums, galleries, and hospitals[41]. The combination of violet LDs with phosphor-excited white light sources promises improved luminous efficiency and CRI[42]. The latest development presents a violet LD with over 5-W output power at 405 nm and a peak WPE of ~42%[43].

3. Subsystem

The conversion of monochromatic light to white light is essential for laser-based lighting, displays, and communications. The subsystem for generating white light is discussed in this section. There are different approaches to generating white light, as illustrated in Fig. 4. Generally, white light can be generated by mixing the emissions from different LDs, or by color conversion.

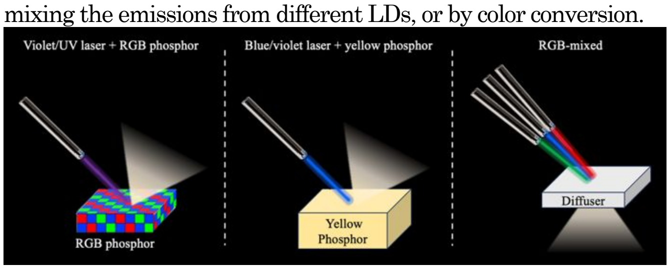

Figure 4. Demonstration of different ways of forming laser-based white light source.

RGB Mixed White Light Source. The scheme of mixing RGB LDs into a laser-based white light was proposed in 2002[44]. The RGB-generated white light offers a higher CRI and correlated color temperature (CCT) than those emitted by phosphor-coated blue LEDs, which reveals a better capability in lighting and display applications. Researchers have demonstrated that illumination with four monochromatic lasers is perceptually equivalent to a continuous-spectrum white reference illuminant when observed by the human eye[45]. Utilizing color-mixed laser light allows customization to meet human or economic preferences regarding chromaticity, color rendering quality, or health. To obtain a higher CRI for laser lighting, Neumann et al. applied another yellow laser to form the white light[46]. The CRI can be further increased to over 85 by utilizing violet LD and yellow LED in addition to RGB LD[47]. Fan et al. also explored multi-color in a monolithic structure to generate white light through a nanomaterial growth strategy[48].

Color-Conversion Based White Light Source. Luminescent-based color conversion involves the concepts of Stokes shift (down conversion) and anti-Stokes shift (up conversion), where luminescent materials absorb light from the lasers and then emit light at different wavelengths. With the development of emerging luminescent materials such as perovskites[49], metal-organic frameworks (MOFs)[50], organic fluorophores[51], etc., the utilization of the color-converting technique extends the versatility of laser lighting. The facile synthesis/fabrication process and unique photophysical properties of the luminescent materials facilitate various practical applications, including enhanced white-light illumination[52], omnidirectional transmitters[53], light amplification[54], energy harvesting[55], fluorescent sensing[56], and so on. As an example shown in Fig. 5(a) and (b), when mixing blue excitation light with the fluorescence from perovskite nanocrystals and red phosphor, high-quality white light was generated for simultaneous illumination and high-speed communication[57].

An emerging application for incorporating color-converting luminescent materials with lasers is in optical wireless communication. One primary function is to manipulate the wavelength of the transmission signal to enhance channel capacity and align with the higher responsivity region of conventional Si-based photodetectors[58]. This can be achieved by integrating luminescent material with light sources (transmitters). For improved communication performance, color-converting materials with short fluorescence lifetimes, high PL quantum yield, high absorption coefficient, and a large Stokes shift are generally required[59]. Capitalizing on their high structural and photophysical tunability, RGB perovskite-based color converters were fabricated and demonstrated to enable aggregate Gb/s visible-light communication[60]. Furthermore, through precise structural adjustments, a series of MOFs emitting blue and green light were synthesized to be applied in color-pure wavelength-division multiplexing (WDM) (see Fig. 5(c)). Individually pumped by 375-nm and 405-nm lasers, high-speed data transmission with low crosstalk between two channels was achieved[61]. Another significant role of color conversion in laser-based OWC systems is to overcome the étendue limit during the light collection. Due to the high coherence and directionality of laser beams, maintaining strict alignment with small-area high-speed photodetector can be challenging. Especially when using passive focusing optics, the field of view will be sacrificed with increased optical gain. In this regard, luminescent materials can circumvent this limitation by decoupling the field of view and offering optical gain through spontaneous emission. The luminescent materials can be fabricated into planar film or scintillating fibers, offering remarkable light guiding, flexibility, and improved functionalities in the applications of WDM[62], turbulent underwater wireless optical communication (UWOC)[63], large-area wide-field-of-view detection[64, 65], and precise beam tracking[66]. Since laser safety is gaining great attention, in blue laser-pumped phosphor-based systems, the white light output is highly divergent and no longer has a destructive power[1]. Studies have demonstrated that through proper engineering design, a laser-pumped phosphor-based system with a 5000 lm output can effectively reduce speckle contrast to as low as 1.7%, thereby minimizing the safety risk caused by visual disturbance[67].

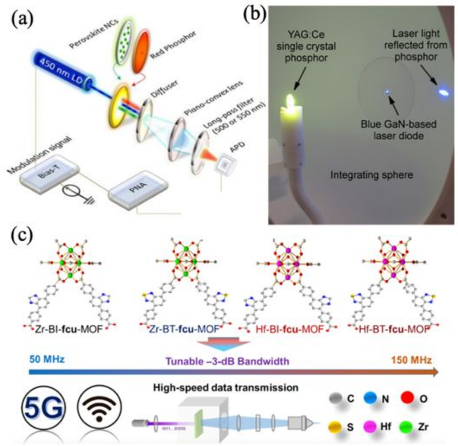

Figure 5. Phosphor materials used to generate white light. (a) perovskite-based green phosphor with red phosphor [57] Copyright 2016 American Chemical Society, (b) single crystal YAG:Ce phosphor [52] ©2016 Optica Publishing Group, (c) metal–organic frameworks based phosphor for WDM, reprinted with permission from[61]. Copyright 2023 American Chemical Society.

4. System

Basic VLC System. Figure 6 illustrates a typical experimental system for testing the performance of VLC devices and systems in the laboratory. At the transmitting end, the signal is generated and then transmitted via an arbitrary waveform generator (AWG), amplified using an electrical amplifier, and coupled with a DC current supply to drive the light source. At the receiving end, a lens is used to collect the light, which can enhance the signal-to-noise ratio of the received signal. The photodetector converts the optical signal into an electrical signal, which is then sampled using an oscilloscope. The received signal is subsequently sent back to the computer for offline processing and bit error rate (BER) calculation. Different modulation techniques have been investigated in VLC system, including on-off keying (OOK), pulse amplitude modulation (PAM), orthogonal frequency-division multiplexing (OFDM), carrier amplitude phase (CAP), discrete multitone (DMT), etc.[68].

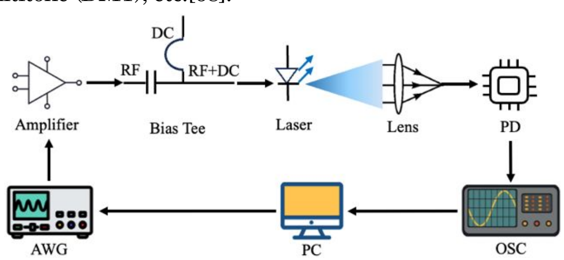

Figure 6. A typical VLC lab testing system setup

Recent years have witnessed a rapid development of laser-based VLC systems with higher data transmission rates and longer channel distances. The key findings and performance parameters of recently demonstrated VLC systems are summarized in Table 1.

Table 1. Comparison of illumination and communication performance of laser-based VLC systems.

Type	CCT	CRI	Data rate	Distance	Year	Ref.
RGB	5835 K		4.4 Gbps	0.2 m	2015	[69]
RGB	8000 K		14.0 Gbps	0.3 m	2015	[70]
RGB	8382 K	54.4	8.8 Gbps	0.5 m	2017	[71]
RGB	6500 K		11.2 Gbps	0.5 m	2018	[72]
RGB			20.2 Gbps	1.0 m	2018	[73]
RGBV			35.0 Gbps	4.0 m	2019	[74]
RGV-Y	4852 K	71.6	28.4 Gbps		2020	[75]
RGB-Y	3503 K	90	11.7 Gbps	0.5 m	2022	[76]

Using 16-QAM (Quadrature Amplitude Modulation) scheme, in conjunction with red, blue and green LDs, the white light system showed red LD with the highest data rate of 4.4 Gbps, while the blue and green LDs also exceeded 4 Gbps[69]. Wu et al. realized a transmission data rate of 8.8 Gbps over 0.5 m in an RGB-LD mixed WDM-VLC system, generating white light with a CRI of 54.4[71]. Yellow LED will contribute to CRI in a mixed white light system[75]. A phosphor plate can significantly raise the CRI at work [76], while CRI was successfully enhanced to 90 by adding the additional red and green LD spectrum, with the data rate maintaining over 11 Gbps. Utilizing a compact tricolor laser transmitter, Hu et al. demonstrated an RGB LD-based VLC system with a recorded data rate of 46.41 Gbps[38]. Both the data rate and the illumination indicators for the RGB mixed white light communication system are steadily improving. By adding more lasers with different wavelengths, Luo et al. achieved over 100-Gbps free-space VLC based on 10-λ laser WDM[77, 78]. Laser-based white light is expected to find its unique applications in high bit rate wireless data links in the near future.

In addition to its use in emitter structures, the Si-substrated GaN/InGaN multiple-quantum-well (MQW) structure can also be utilized for photodetectors. A 4×4 array micro-PD and a 2×2 array is employed in MIMO-VLLC links operating at 405 nm, achieving data rates of up to 13.2 Gbps[79].

Underwater Communication System. Water covers more than 70% of the Earth's surface, including uncharted areas in the deep sea, making underwater wireless optical communication (UWOC) a subject attracting increasing research interest in recent years. UWOC offers substantial advantages, including a larger modulation bandwidth compared to acoustic communication and lower attenuation compared to RF communication. As a result, it has spurred progress in marine life exploration, underwater environmental monitoring, and offshore industries. Nakamura et al. first propose the application of blue GaN laser for underwater communication[80]. Laser-based UWOC systems, unlike incoherent light sources of LEDs, enable long transmission distances, high modulation bandwidth, and excellent power. Table 2 provides a comparison of the performance of LD-based UWOC over the past five years. Notably, within the low-attenuation 'blue-green' window (i.e., 450-550 nm) of seawater, laser lighting in the blue-to-green spectral range is generally preferred. However, different underwater environments and turbulence conditions can lead to variation in the absorption coefficient across different wavelengths, necessitating a diverse range of light sources for adaptive operation[81].

Moreover, underwater environment is highly dynamic and unpredictable, which creates obstacles to achieving accurate point-to-point optical signal transmission and reception. To address this, mitigating constraints related to positioning, acquisition, and tracking (PAT) is essential. Leveraging the scattering properties of UV light, Sun et al. demonstrated a non-line-of-sight (NLOS) UWOC system by using a 375-nm UVA laser as the transmitter, alleviating the need for precise alignment between transmitter and receiver in LOS UWOC[82]. Subsequently, a wide-beam Laser-based white light system was deployed for diffuse-LOS optical communication across the water-air interface. Covering an area of 1963 cm2, a net data rate of 9 Mbps was maintained over a 10-m distance once the beam was aligned with the avalanche photodetector mounted on a drone[83]. Weng et al. provided another solution by integrating laser into autonomous underwater vehicles (AUVs) to actively control the direction of the laser beam[84]. Beyond enabling high-speed, long-distance, and reliable data transmission, laser-based lighting has also opened up opportunities for simultaneous energy harvesting[85], turbulence investigation[86, 87], and channel modeling[88, 89], all of which have significantly improved underwater research. Beside conventional blue Gaussian beam, a full-color circular auto-focusing Airy beams metasurface transmitter was introduced for reliable, large-capacity and long-distance UWOC links to increase data transmission rate of 91%[90].

Table 2. Comparison of LD-based UWOC performance in the recent five years.

Wavelength	Data Rate (Modulation Scheme)	Transmission Distance	Year	Ref.
RGB	Aggregate 9.4 Gbps (OOK)	2.3 m	2018	[91]
680 nm	25 Gbps (NRZ-OOK)	5 m	2018	[92]
520 nm	500 Mbps (NRZ-OOK)	100 m	2019	[93]
480 nm	30 Gbps (PAM4)	15 m	2019	[94]
450 nm	5.36 Gbps (OFDM)	2.4 m	2020	[95]
520 nm	3.31 Gbps (OFDM)	56 m	2020	[96]
Blue & green	200 Mbps (OFDM)	120 m	2021	[97]
520 nm	1 Gbps (PAM4)	130 m	2021	[98]
450 nm	5 Gbps (DFT-S DMT)	50 m	2021	[99]
450 nm	2 Gbps (NDFE)	55 m	2022	[100]
450 nm	660 Mb/s (I-SC-FDM)	90 m	2023	[101]

* NRZ: non-return-to-zero
NDFE: nonlinear decision-feedback equalizer
I-SC-FDM: interleaved single-carrier frequency division multiplexing

Towards Wide Field-of-View System. Point-to-point systems are commonly used in VLC experiments, but wide-coverage systems are crucial for practical applications. LEDs offer a wide field-of-view (FOV), ensuring extensive lighting coverage. Consequently, an LED-based VLC system enables a robust wireless optical connection between the transmitters and the mobile receivers. LDs have advantages including high-speed, long-range, and high-power. However, traditional laser-based VLC systems face significant limitations in application due to their high directivity, which requires a complex pointing mechanism.

Although enlarging the active area of a photodetector (PD) is considered an effective way to gain a larger transmitting FOV, there is a tradeoff between the receiving area and its modulation bandwidth. Researchers put forward various optical structures to overcome this hurdle at the receiving end. A sandwich structure light-trapping fluorescent antenna provided an increase of FOV from 30° to 80° and a significant signal-to-noise gain[102]. Alkhazragi et al. utilized fused fiber-optic tapers (FFOTs) consisting of hundreds of thousands of tapered optical fibers, which can support Gbps data transmission at ±30° acceptance angle[103]. Hou et al. used a fisheye lens to broaden the receiving FOV and established a 34° system with over 3-Gbps high transmitting rate[104]. Applying a silicon photomultiplier (SiPM) as the receiver, Ma et al. realized 500-Mbps data transmission with ultra-wide FOV reaching 180°[105].

In a wide-coverage system, as the angle increases, Rayleigh scattering becomes more prominent, and the received signal power decreases. When the signal power is close to the noise level of the system, even minor nonlinear effects have a significant impact on signal transmission [106]. In addition, amplifiers may operate in their nonlinear range when amplifying low-power signals, making their nonlinear characteristics more pronounced and thus enhancing the system's overall nonlinearity [107]. Low-order modulation techniques, such as OOK and pulse position modulation (PPM), demonstrate enhanced robustness in nonlinear optical environments. These techniques primarily leverage the presence or temporal positioning of optical pulses to encode data, thus minimizing the impact of amplitude and phase variations caused by nonlinear effects prevalent in optical transmission systems. Advanced modulation techniques like OFDM can improve spectral efficiency and system robustness against multipath effects, but high h peak to average power ratio (PAPR) of OFDM signals may push the signal into the nonlinear region of LEDs, increasing system nonlinearity. To solve this, Cao et al. developed a frequency domain equalization algorithm based on reservoir computing (RC) that simplifies neural network training by training only part of the network connections, effectively enhancing the transmission performance of VLC systems[108]. DMT is one of the variations of OFDM modulation. In DMT, the modulation depth of each subcarrier can dynamically adjust based on channel quality. This means that in favorable channel conditions, some subcarriers may employ higher-order modulation schemes to increase data rates, while in poorer channel conditions, the modulation order may be lowered to enhance the robustness of the signal.

Despite of the wide-angle structure at the receiving end, the angle of a VLC system is fundamentally limited by the beam divergence angle at the transmitting end. Phosphor in glass is considered a feasible solution to broaden the coverage area of lasers while converting blue laser into yellow to generate white light. Recently, we have been working on a high-power laser-based white light emitter and using it as a transmitter in the VLC system, which is shown in Fig. 7(a). The luminance distribution of the fabricated light source at a distance of 1 m is depicted in Fig. 7(b). The central irradiance of the light source exceeds 650 lx, while the overall irradiance distribution shows a gradual decrease from the center toward the margin, with great symmetry. Utilizing bit-loading DMT modulation technology, a laser-based white light VLC system has been constructed. By moving the location of the receiver, we experimentally measured the data transmission rate when the receiver was placed at different distances and angles from the transmitter. As can be observed in Fig. 7(c), the transmitting rate is above 1.5 Gbps at a distance of 2 m, when the angle is tilted from -16° to 16°. The peak data rate achieved was 2.8 Gbps with the BER satisfying the forward error correction (FEC) standard.

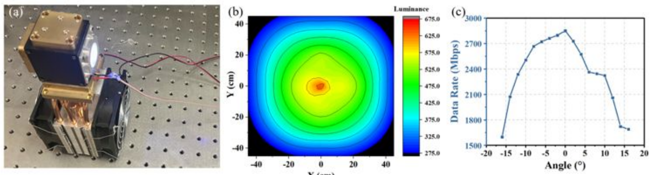

Figure 7. (a) A high-power laser-based white light emitter; (b) the luminance distribution of the laser-based white light emitter at 1 m; (c) measured data transmission rate vs. tilting angle at a transmission distance of 2 m.

5. Applications

With the rapid development of laser lighting and VLC technology, many emerging applications have been utilizing the advantages of such systems. These include metaverse, AR/VR, emergency communication, indoor positioning and navigation, smart lighting, home automation, and intersatellite communication, etc. In this section, a few of the novel applications will be discussed.

6G Multi-Frequency Band Converged Networking. With the evolution of mobile communication networks, the future 6G networks are set to feature characteristics of multi-bands, multi-formats and multi-scenarios. Different frequency bands, including sub-6GHz, millimeter wave, terahertz wave, and visible light wave, will collaborate to provide improved services across 6G scenarios[109]. Various network formats like long-term evolution (LTE), WiFi, and 5G will be multi-dimensional deployed in diverse scenarios to achieve full coverage[110]. VLC networks are considered a potential solution for wider bandwidth in 6G, often seen as a complement to RF networks to enhance overall network coverage.

In the context of multi-frequency network hybrid deployment, VLC serves as a supplement to WiFi, requiring a certain field of view to seamlessly integrate with other access methods. Additionally, there are certain bandwidth requirements for LD transmission, leveraging the rate advantages of LD to complement WiFi and 5G technologies. Advancements in LDs with wider fields of view and enhanced transmission rates are poised to significantly bolster VLC network coverage, reduce network shadow areas, and support cell-edge user. The expanded capabilities of these LDs are expected to extend the application scenarios from confined indoor spaces to vast indoor hotspots, including areas such as airport lounges, stadiums, and shopping malls. With Gbps-level data transmission capabilities, these LDs can directly replace WiFi access points (APs) and home-based femtocells, offering a novel solution for access networks.

Vehicle-to-Vehicle Communications. A longer illumination range with extremely bright and concentrated light beam inevitably makes laser the best option for car headlights. BMW reported laser headlights 10 times more intense than conventional sources, while boosting energy efficiency by 30 percent above LEDs[111]. The use of lasers in car headlights also enables high-speed data transmission within vehicles, thus relieving escalating urban traffic and safety challenges and providing a feasible implementation for intelligent transportation systems (ITS).

Within the expanding employment of VLC in vehicular communication, several pivotal studies have illuminated the development of this technology. Applying 64 QAM-DMT on a car headlamp, a transmitting data rate of 375 Mbps and 427.5 Mbps can be obtained in [112] and [113] respectively. Geometrically shaped amplitude phase shift keying can make further efforts to improve the communication data rate to 660 Mbps[114]. Wang et al. designed a 2×2 PIN PD array with deep-neural-network post-equalizers, and first raised the headlight based transmitting data rate beyond 1 Gb/s at a 4-m distance[115]. Although the above work was conducted in the laboratory without considering the impact of the environment, a breakthrough was made by Li et al., who demonstrated a 100-m outdoor vehicular VLC system supporting over 300 Mbps transmission in both day and night[116].

Together, these studies underscore the current capabilities of laser-based VLC in ITS and their potential for future advancements. In ITS, high-power light source is required to propagate over sufficient distances. Simultaneously, the transmission rate is also crucial, especially for vehicle-to-vehicle communication which emphasizes timeliness, necessitating the use of LD's large bandwidth to achieve this. However, challenges such as environmental interference and infrastructure integration remain. In vehicle-to-vehicle communication applications, more complex communication channels and intelligent networking strategies in ITS require further research.

Electromagnetic-sensitive Scenario Communications. With the transmission characteristics of wireless optical signals, in electromagnetic-sensitive environments such as in-flight communications, hospital communications, and transformer station communications, VLC offers several advantages over traditional communication technologies, particularly in terms of security and interference reduction. Novel LDs with enhanced data transmission rates and improved illumination capabilities offer the concurrent integration of communication and lighting functionalities in the aforementioned scenarios. For instance, the deployment of compact, low-power LDs in internal aircraft communication facilitates the mitigation of challenges associated with aircraft modifications, all while preserving performance levels. In microwave dark rooms, VLC emerges as a reliable technology, furnishing a stable communication link for testers. Furthermore, in environments demanding both optimal lighting conditions and electromagnetic shielding, high-rate LDs prove instrumental in facilitating high-speed data interaction among diverse medical devices within hospital operating rooms and similar settings. Medical illumination, image display and communication are important fields for laser fusion applications.

Research has proven that a yellow phosphor with a fiber-coupled blue-violet diode laser can provide better image quality over existing endoscopic light sources, and has the advantages of compact design, improved ergonomics, and more uniform illumination[117]. Plastic optical fiber (POF) has a broad numerical aperture and significant attenuation, affects more in medical environments, especially endoscopy, where optimal image clarity is paramount. Huang et al. proposed an innovative 100-m POF transmission system that coalesces a visible red laser with a cascaded neural network post-equalize, addressing nonlinear distortions inherent to POF [118]. While this research enriches the understanding of POF transmissions, it holds broader implications in endoscopic technologies. However, challenges persist that future endeavors should focus on robust system designs, increasing transmission fidelity, and seamless integration into clinical environments. The study of laser hybrid applications offers a vision of transformative innovations in medical diagnostics and procedures.

Wearable Devices. Though significant advancements in VLC systems have been achieved with LEDs as a primary light source, the potential of using LDs in the wearable domain remains largely unexplored. Researchers have leveraged LED technology in wearable VLC devices, paving the way for health monitoring combined with data communication. Kim et al. integrated VLC into fashion wearables for health data transmission[119]. Rachim et al. designed a system that transmits wearable sensor data via LEDs to smartphones for analysis and cloud storage[120]. While LEDs have already been demonstrated for wearable electronics, LDs may contribute to applications with higher modulation bandwidth and improved spectral purity. Furthermore, LDs' integration in "Smart Fashion" can enable longer communication ranges and even faster data exchanges, catering to broader applications beyond just personal health monitoring. Meanwhile, eye safety matters of LDs need to be taken into concern.

With the solid foundation of LED-based wearable systems, the inherent advantages of LDs can revolutionize data transmission rates, communication accuracy, security, and energy efficiency in wearable technology. With the characteristics of large bandwidth, high throughput, low latency, and multi-connectivity of VLC, the novel LD is expected to support VLC networks to further realize the XR scenario. The compact size of receiver devices simplifies the integration of XR peripherals, while the centimeter-level positioning accuracy proves adequate to enable XR for a diverse range of finely detailed applications. The next era of wearable VLC could very well be laser-driven, marking a confluence of fashion, healthcare, and cutting-edge optical communication.

6. Conclusions and Outlook

Laser-based white light has incomparable advantages in the integration of lighting, communication, and display for its high efficiency, ultrafast transmitting rate, and color fidelity. In this review, we shed light on the state of the art in laser-based white light technology, exploring the latest developments, key challenges, and the exciting possibilities that lie ahead in the lighting, displays, and communication hybrid applications. Several specific challenges and the corresponding possible solutions for laser-based VLC systems are summarized in Fig. 9. As research and development continue, we can expect to find innovative solutions that leverage laser-based white lights for more energy-efficient and high-performance lighting, stunning visual displays, and secure data communication. The advancing technology has the potential to revolutionize various industries, from smart cities and autonomous vehicles to entertainment and healthcare, thereby creating a more connected and immersive future.

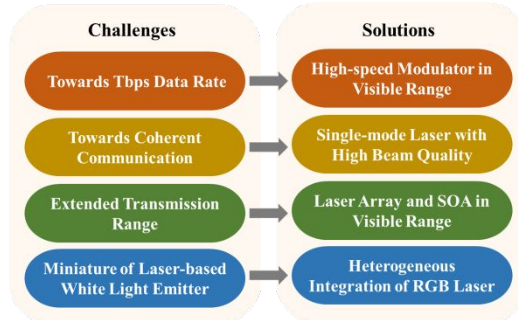

Figure 8. Challenges and possible solutions for laser-based VLC system.

Moving forward, several challenges remain to be addressed. Firstly, facing the burgeoning demand for Tbps-level data communication, challenges persist in narrowing the substantial data rate gap between VLC and telecommunication based on near-infrared LDs. Other than direct modulating the LDs, external modulators can be explored to take a step forward with extended modulation bandwidth. In addition, there is a lack of high beam quality devices for coherent communication. In particular, single longitudinal mode laser with narrow linewidth requires more research and technological breakthroughs. Meanwhile, there is a need to develop suitable amplifiers and laser array structures to amplify signals and extend communication distances, which is crucial to realizing the full potential of visible laser communication in the pursuit of long-range, high-speed data transmission. Moreover, the miniature and integration of white lasers present a unique set of challenges. Efforts have to be made to achieve the heterogeneous integration of RGB three-beam light by dealing with the complex structure design. Wang et al. have proved that a spherical concave micro-mirror might be a vertical coupling solution[121]. We are working on the integration of III-nitride photonic devices towards visible light photonic integrated circuits. The eventual realization of a compact, energy-efficient, low-cost and high-speed laser-based VLC system will pave the way toward a smart way of life in the 6G era.

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