

# Visible Lasers and Emerging Color Converters for Lighting and Visible Light Communications

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**Abstract:** GaN-based lasers are promising for white lighting and visible-light communication (VLC). The advances of III-nitride photonic integration, and the application of YAG crystal and perovskite-based phosphors to lighting and VLC will be discussed.

**OCIS codes:** (060.2605) Free-space optical communication; (140.7300) Visible lasers; (230.3670) Light-emitting diodes; (230.5590) Quantum-well, -wire and -dot devices; (250.0250) Optoelectronics; (250.5960) Semiconductor lasers.

The past decade witnessed the rapid development of III-nitride light-emitting diodes (LEDs) [1, 2], superluminescent diodes (SLDs) [3, 4], and laser diodes (LDs) [5, 6], for solid-state lighting (SSL), visible-light communication (VLC), optical storage, and internet-of-things (IoT) [7, 8]. InGaN/GaN quantum well (QW)-based LEDs have been established as the fundamental component for SSL applications while recent studies suggested that the GaN-based LDs, which is free from efficiency droop, may outperform LEDs as a viable high-power light source [9, 10]. Meanwhile, there are increasing potentials in using such emitters in visible-light based optical communication systems for indoor and outdoor applications as data-rate demands are exponentially growing in the near future [8, 11, 12]. Since LDs exhibit significantly larger modulation bandwidth than LEDs, VLC links based on GaN lasers have shown multiple gigabit per second (Gbps) data rate, suggesting its growing potential for SSL-VLC dual-functionality applications [12, 13]. The development of devices and components in laser-based white lighting and data communication systems will be discussed.

Similar to the structure in white LEDs, laser white light bulb can be constructed by employing a blue laser exciting yellow phosphor as the color converter. A correlated color temperature (CCT) of  $\sim 4000$  K and a color rendering index (CRI) of  $\sim 57$  has been achieved using a 450-nm emitting LD and YAG:Ce phosphor [13, 14]. The CRI and CCT can be further improved or engineered by using combinations of violet-blue LDs with a mixture of two or more color converters. For example, a CCT of  $\sim 2700$  K and a CRI of  $> 90$  has been reported using a violet LD exciting a mixture of red-, green-, and blue-emitting (RGB) phosphors [14]. By using a blue LD with novel CsPbBr<sub>3</sub> perovskite nanocrystals (NCs) with conventional red phosphor as the color converter, a CRI of  $\sim 89$  and a CCT of  $\sim 3200$  K has been achieved [15]. Apart from the white light characteristics including CRI and CCT, the conversion efficiency and stability of color converters are of particular interest due to a significantly higher excitation power density in LD based white lighting [16]. Hence, the utilization of YAG:Ce single crystal phosphor plate has been investigated for high power laser based SSL lamp reaching a peak luminous flux of 1100 lm [17]. Ceramic YAG:Ce yellow phosphor plates have also been developed for efficient white light conversion under high power blue radiant flux density of 19.1 W/mm<sup>2</sup> [18]. The YAG crystal and perovskite-based phosphors offer new opportunities for the future of laser based high brightness lighting. Further investigations on effects of the surface morphology, diffusing element and shape of the color converter are important in engineering the white light beam excited by focused high power violet-blue lasers.

The utilization of white light for VLC, or “Li-Fi”, has attracted increasing research interest owing to the growing demand for high-speed data links [8, 11]. We have demonstrated 2 Gbps data transmission of unfiltered white light generated by direct modulation of a blue GaN LD exciting YAG phosphor using a non-return-to-zero on-off keying (NRZ-OOK) modulation scheme [19]. A 3-dB modulation bandwidth of 1.1 GHz was measured without a limitation from the slow 3.8 MHz phosphor response, which is significantly higher than that in conventional LEDs. High-speed data communication link based on white light generated using a violet LD pumping RGB phosphors was also demonstrated recently [20]. Further investigations show that both GaN-based edge emitting laser diodes (ELEDs) and vertical-cavity surface-emitting lasers (VCSELs) exhibit beyond GHz modulation bandwidth [21, 22]. Though the micro-pixel LEDs have shown enhanced modulation characteristics compared to the broad-area counterparts, their output powers are relatively low, making it less attractive for high brightness applications [23, 24]. Therefore, the GaN laser-based VLC will play an important part in free space optical communications.

To date, the smart lighting and VLC functionalities have been demonstrated based on discrete devices, such as III-nitride LDs, transverse-transmission modulators, and planar photodetectors [25, 26]. We have studied the monolithic integration of LDs together with modulators, amplifiers, and detectors, for VLC applications. Such on-chip integration offers a number of advantages, including small-footprint, high-speed, and low power consumption. A blue-emitting

integrated waveguide modulator-laser diode (IWM-LD) has been designed on a semipolar ( $2\overline{0}\overline{2}\overline{1}$ )-plane GaN substrate [27]. The IWM-LD show a high modulation efficiency of 2.68 dB/V. A large extinction ratio of 11.3 dB is measured in the violet-emitting IWM-LD [28]. Utilizing the integrated modulator, Gbps data communication was demonstrated using OOK modulation scheme. In addition, we fabricated the 404-nm emitting integrated short-wavelength semiconductor optical amplifier (SOA) - laser diode, showing a large gain of 5.32 dB at 6 V [29]. Such device can also be utilized in the modulated amplifier scheme enabling high-speed modulation. Since the signal detection is another important component in VLC system, we have fabricated and characterized the high-performance waveguide photodetector (WPD) integrated LD at 405 nm [30]. A significant large modulation bandwidth of 230 MHz is measured in the WPD and can be further improved by reducing the RC-time constant. Both the WPD and LD are sharing the single active region, making it promising to build VLC transceiver on single laser chip. The seamlessly integrated elements enable photonic IC at the visible wavelength for many critical applications, such as smart lighting and display, free-space and underwater optical communications, optical switching, clocking, and interconnect [20, 31-33].

In summary, the paper presents the advances and challenges of laser based SSL-VLC systems. The design, fabrication, and characterization of III-nitride laser based photonic integration and emerging color converters for lighting and data communication are discussed. The results suggest that the laser-based solution is a promising approach towards next generation high-brightness smart lighting and high-speed visible-light communications.

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