High-power blue superluminescent diode for high CRI lighting and high-speed visible light communication

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Abstract: We demonstrated a high-power (474 mW) blue superluminescent diode (SLD) on c-plane GaN-substrate for speckle-free solid-state lighting (SSL), and high-speed visible light communication (VLC) link. The device, emitting at 442 nm, showed a large spectral bandwidth of 6.5 nm at an optical power of 105 mW. By integrating a YAG-phosphor-plate to the SLD, a CRI of 85.1 and CCT of 3392 K were measured, thus suitable for solid-state lighting. The SLD shows a relatively large 3-dB modulation bandwidth of >400 MHz, while a record high data rate of 1.45 Gigabit-per-second (Gbps) link has been achieved below forward-error correction (FEC) limit under non-return-to-zero on-off keying (NRZ-OOK) modulation scheme. Our results suggest that SLD is a promising alternative for simultaneous speckle-free white lighting and Gbps data communication dual functionalities.

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1. Introduction

Ever since the first demonstration of ambient-sunlight wireless telephone communication [1], the field of optical wireless communication has evolved significantly. The recent advent of light-emitting diode (LED) and laser diode (LD) allows one to integrate efficient solid-state lighting (SSL) and high-speed visible light communication (VLC), offering data security and immunity to electromagnetic interference [2]. Beyond this, VLC provides the resource for mitigating the saturating bandwidth in the conventional radio-frequency (RF) band. The RF spectrum is limited to a bandwidth of ~300 GHz, which is significantly lower than the predicted bandwidth demand of 6 THz by 2035 [3], and ~1300 times lower than the bandwidth available in the visible light spectrum (~390 THz) [3,4]. Moreover, in the past 10 years, data transmission rate in VLC systems have remarkably improved from Megabit-per-second (Mbps) to Gigabit-per-second (Gbps) offering unprecedented possibilities of simultaneous functionalities in signaling, communication, localization, and illumination for the paradigm-shift in 5G technology [3,4] and beyond.
Light emitters are essential components in VLC, deserving a focused attention in order to push the limit for higher data rate and modulation bandwidth. Although Gbps-class high-speed data transmission based on LD has been reported [5–9], the speckle-noise and the concern for eye-safety remain as some of the existing challenges for practical implementation in SSL-VLC systems. Similarly, LED-based emitter have also been studied and demonstrated in SSL-VLC [10–12]; however in order to achieve high data rates, the LED-based VLC technology has to resort to complex modulation schemes and/or multiplexing configurations.

Group-III-Nitride-based superluminescent diodes (SLD) have received significant attention recently [13–16] owing to their unique features, which combine the advantages of both LEDs and LDs [17]. The short wavelength SLDs, have a broad spectral emission attributed to the coexistence of spontaneous and stimulated emission, known as amplified spontaneous emission (ASE) [18], making it a promising alternative for SSL-emitters. In parallel, highly directional beam (limited etendue) with high power, low speckle noise and droop-free can be achieved [19]. Conventionally, SLD is used in optical coherence tomography (OCT) [20], fiber gyroscope [21], sensing [22], and picoprojections [23]. Our previous works reported the fabrication of semipolar InGaN-based SLDs and the potential for white light generation with a CRI of 68.9 [19] and for data communications [24,25] However, the limited availability and high-cost of semipolar GaN substrate present significant challenges in eventual foundry adoption. Therefore, it is important to develop high-power blue SLD based on matured and relatively low-cost c-plane GaN substrate and fabrication technologies.

In this work, we present a high-power (>100 mW), broad spectral emission (6.5 nm) blue (442 nm) SLD on c-plane GaN substrate. The device shows a large 3-dB modulation bandwidth of >400 MHz and a record SLD data rate of 1.45 Gbps based on on-off keying (OOK) modulation. Integrating SLD with a commercial phosphor generates high quality white light with a color rendering index (CRI) of 85.1 and correlated color temperature (CCT) of 3392 K. Additionally, a record-breaking high-power of 474 mW was achieved under pulsed injection (2% duty cycle, 9.8 kHz). This is the first report on simultaneous attainment of high performance SLD characteristics for white-light communication, such as high power, color quality, modulation bandwidth and data rate, while droop-free, simply based on c-GaN substrate-platform, thus advancing SLD as a practical utility for simultaneous SSL-VLC technology.

2. Experimental setup

Various methods have been pursued to realize high-power SLD where the underlying mechanism is to suppress the formation of resonance cavity, such as implementing antireflection (AR) facet coating [26], tilting or bending the waveguide and facet [14,27,28], and utilizing a passive absorber [29]. In our work, we utilize a 12° tilted-facet as illustrated in Fig. 1(a), etched from a GaN-based 15-µm-wide ridge blue LD with a ~1 mm long waveguide. This tilted angle was adopted to minimize the reflectance from the front facet of the SLD without antireflection coatings (AR) [30], while the back facet is coated with a dielectric high-reflective (HR) mirror with >90% reflectivity in order to increase the output power. Conventional LD fabrication steps were used in a commercial epitaxial structure consisting of a c-plane GaN substrate, AlGaN p- and n-type cladding layers, InGaN active region with multiple quantum wells, p-AlGaN electron blocking layer, highly Mg-doped p-GaN contact layer and GaN waveguides similar to previous reported structures [31].

The light-output – current – voltage (L–I–V) characteristics of the SLD device were measured up to 1 A in both continuous wave (CW) and pulsed mode (2% duty cycle, 9.8 kHz) using a customized probe station equipped with a Keithley 2520 pulsed laser diode system, a Labsphere integrating sphere, and a thermoelectric cooler (TEC) to stabilize the operation at room temperature (18 °C to 22 °C). The electroluminescence (EL) spectra measurement was conducted using an Ocean Optics HR4000 spectrometer. The generated
white light from combining the SLD and a commercial phosphor-plate 930-LR from ChromaLit Linear Intematix was characterized using a GL-Spectis 5.0 Touch from GL-Optic, and the illumination was measured using a Uni-T UT383 meter. The frequency response was measured using an Agilent E8361C PNA network analyzer. An Agilent 85093-60010 RF electronic calibration (E-cal) module was utilized for the calibration process. The data transmission experiment was conducted using the non-return-to-zero on-off-keying (NRZ-OOK) pseudorandom binary sequence (PRBS) 2^10-1 data stream from the Agilent N4903B J-BERT pattern generator. The setup involves a Tektronix PSPL5580 bias tee, a Tektronix PSPL5866 linear amplifier, and a Menlo Systems APD210 Si avalanche photodetector as the receiver. Also, the eye diagrams were captured using an Agilent DCA-86100C digital communication analyzer during the NRZ-OOK data transmission measurement.

3. Results and discussion

The EL spectra of the SLD at different injection current are shown in Fig. 1(b). The change in the peak position and full-width at half-maximum (FWHM) of the SLD emission are summarized in Fig. 1(c). FWHM decreases from 20 nm to 6.5 nm on increasing injection current from 100 mA to 1 A respectively. Broad FWHM (6.5 nm) even at high injection currents (1 A, CW) confirm that the SLD is working in ASE regime. Such spectral narrowing is expected and attributed to the higher ASE near the peak optical gain of the active region [32]. Furthermore, initial blue shift is observed in the EL peak position of the SLD, which is mainly attributed to the band-filling effect, with a further red-shift in the peak positions at higher currents due to the increase in device heating.
Table 1. Comparison of characteristics on GaN-based superluminescent diodes (SLDs).

| λ  (nm) | Substrate material | Waveguide design (ridge width, w; cavity length, l) | Optical power (mW) | Spectral FWHM (nm) | Optical power · FWHM (mW·nm) | Year | Ref. |
|--------|--------------------|---------------------------------------------------|-------------------|-------------------|-----------------------------|------|------|
| 405    | Semipolar GaN      | 45° tilted facet (w = 4 μm, l = 590 μm)           | 20 (CW)           | 9                 | 180                         | 2016 | [24] |
| 405    | c-GaN              | 5° tilted waveguide (w = 3 μm, l = 700 μm)        | 0.65 (pulsed)     | 5.23              | 3.4                         | 2010 | [33] |
| 405    | c-GaN              | 10° tilted facet, tapered waveguide, back HR coating (dimensions are unavailable) | 200               | 3                 | 600                         | 2011 | [34] |
| 405    | c-GaN              | 5° tilted waveguide (w = 5°10 μm ridge, l = 2 mm) | 125 (CW)          | 2.5               | 312.5                       | 2012 | [28] |
| 405    | c-GaN              | “j-shape” waveguide curved ridge (dimensions are unavailable) | 350 (CW)          | NA                | -                           | 2016 | [35] |
| 405    | c-GaN              | “j-shape” waveguide (w = NA, l = 1 mm)            | 230 (CW)          | 2.5               | 575                         | 2013 | [36] |
| 405    | c-GaN              | “j-shape” waveguide (w = 3 μm ridge, l = 1 mm)   | 200 (CW)          | 2.5               | 500                         | 2015 | [14] |
| 415-423| c-GaN              | “j-shape” graded In composition waveguide (w = 3 μm, l = 1 mm) | 3 (CW), 2 (CW)    | 15.5, 5           | 46.5, 10                    | 2017 | [37] |
| 410-445| c-GaN              | Tilted waveguide (w = 2 μm, l = 800 μm)           | 40 (CW), 55 (pulsed) | 5  | 200                           | 2010 | [39] |
| 420    | c-GaN              | Tilted waveguide (w = 2 μm, l = 800 μm)           | 2.8 (CW), 100 (pulsed) | 4.6 | 13                           | 2009 | [13] |
| 428    | c-GaN              | Active absorber (w = 10 μm, l = 2.6 mm)           | 70 (pulsed)       | 10                | 700                         | 2017 | [40] |
| 439    | m-GaN              | Facet roughening (w = 4 μm, l = 500 μm)           | 5 (pulsed)        | 9                 | 45                          | 2009 | [41] |
| 440    | c-GaN              | Curved waveguide AR/HR coating (dimensions are unavailable) | 150 (CW)          | 4                 | 600                         | 2018 | [15] |
| 442    | c-GaN              | 12° tilted facet (w = 15 μm, l = 1 mm)            | 105 (CW), 474 (pulsed) | 6.5 (CW) | 650                          | 2018 | This work |
| 443    | c-GaN              | Curved waveguide, AR/HR coating (w = 2 μm, l = 1.2 mm) | 100 (CW)          | 2.6               | 260                         | 2013 | [23] |
| 445    | c-GaN              | 30° facet (w = 5 μm, l = 800 μm)                   | NA                | 7.7               | -                           | 2014 | [42] |
| 447    | Semipolar GaN      | Passive absorber waveguide (w = 7.5 μm, l = 1000 μm) | 123 (CW)          | 6.3               | 775                         | 2016 | [19] |
| 500    | c-GaN              | Curved waveguide AR/HR coating (w = 2 μm, l = 1.2 mm) | 4.3 (pulsed)      | 4.4               | 17.6                        | 2012 | [43] |

L–I–V plots are presented in Fig. 1(d) and 1(e) under CW and pulsed injection (duty cycle of 2%, 9.8 kHz). The output power (optical) under both conditions reaches maximum values of 105 mW and 474 mW respectively, where the lower output power under CW injection is
attributed to self-heating effect caused by high injection current, increasing the non-radiative recombinations and carrier escape from the heterostructure [33,44]. The L–I plots prove an exponential dependency of output power at lower injection currents (<700 mA), followed by a superlinear L–I characteristic. These characteristics are translated into droop-free emission with maximum external quantum efficiencies (EQE, \( \eta_{\text{ext}} \)) of 6.74% and 16.91% for CW and pulsed injection respectively (Fig. 1(f)).

It is important to ponder the emission wavelength and the crystal plane of growth in light emitting devices. It is well known that increasing the indium (In) composition of the active region of InGaN-based emitters decreases the quantum efficiency significantly [45], therefore, longer emission wavelengths represent a higher challenge for device operation. Also, it has been shown that piezoelectric effects found in c-plane GaN affect the performance of the light emitters [46] and semipolar/non-polar GaN substrates can be a solution, however, the high-cost and low availability of these substrates, as compared to c-plane GaN, delay their implementation. Considering these facts whereby we can ponder the information listed in Table 1, and compare the product of optical power and FWHM among the reports, it can be shown that our SLD device stands out among all previous results.

![Fig. 2. Light beam of LD and SLD: (a) LD beam path. (b) SLD beam path. Insets are the far field projections of the LD and SLD beam patterns, respectively.](image)

The performance of the SLD in generating white light was evaluated based on the speckle density and high-CRI value. In Fig. 2, we compared the emission path and far-field projection of the SLD against a blue LD from the same epitaxial structure and dimensions. The emission path of LD and SLD are shown in Fig. 2(a) and 2(b) respectively where the insets in each of the figures illustrate the far field projection of the devices. Owing mainly to the incoherence nature of ASE and the broader emission (6.5 nm) as compared to the LD (<2 nm), the speckles in the case of LD are denser than those in SLD, which makes SLD promising for the generation of high-power speckle-free white light.

A commercially available phosphor (ChromaLit Linear Intematix) was integrated with the blue SLD to generate white light obtaining an illuminance of 1550 lux measured directly at the source under 1 A CW injection (Fig. 3). Thus generated white light presented a CRI of 85.1, a CCT of 3392 K, and corresponding Commission Internationale de l'Eclairage (CIE 1931) chromaticity coordinates at (0.3991, 0.3625). These values were consistent at different SLD injection current ranging from 700 mA to 1 A. Moreover, the CRI value obtained in this report is significantly higher than our previously reported value of SLD-based SSL on semipolar GaN substrate [19]. In the search for warmer SSL-based white light due to health
concerns \[47,48\], the CCT of 3392 K obtained in this work represents one step further on integrating blue emitters into indoor lighting solutions offering warm illumination with a competent CRI (>85).

![Figure 3. SLD-based SSL white light characteristics: (a) Photograph of SLD in combination with a phosphor plate operating at 1A CW. (b) Illuminance of the generated white light at different injection current. (c) Spectral shape of the white light with CRI of 85.1 and CCT of 3392 K. (d) CIE diagram showing the chromaticity coordinates of the generated white light.](image)

The modulation bandwidth capability of the SLD was explored and plotted in Fig. 4(a). By increasing the current density \(J\), it is expected that the active region carrier concentration \(N\) increases, leading to a decrease in the differential carrier lifetime \(\tau\) \[49,50\]. This differential lifetime is inversely proportional to the frequency modulation bandwidth \(f_{3dB}\), given by \(f_{3dB} = \frac{\sqrt{3}}{2\pi\tau}\), leading to incremental modulation bandwidths at higher injection currents \[51,52\]. The 3-dB modulation bandwidth of our device was measured to be 376 MHz, 398 MHz, and 404 MHz, at 800 mA, 900 mA, and 1A respectively. As shown in Fig. 4(a), the natural frequency response of the SLD shows a continuous flat response without the need of equalization techniques \[53\]. This bandwidth flat response is desired when using modulation schemes for high density data such as orthogonal frequency division multiplexing (OFDM) \[54,55\]. Moreover, the absence of the relaxation resonance frequency peak \(\omega_r\), which is characteristic of LD cavities \[56\] is one more evidence of the existence of ASE and the suppression of the resonance cavity.

Furthermore, we measure the VLC data rate using NRZ-OOK modulation scheme. As seen in Table 2, we demonstrated data rates up to 1.45 Gbps with corresponding bit error rate (BER) of \(1.8 \times 10^{-3}\), which is below the forward error correction (FEC) limit of \(3.8 \times 10^{-3}\). The distance between the emitter and the receiver was ~25 cm. The eye diagrams showing clear open eyes are presented in Fig. 4(b) and 4(c) for two different data rates 1 Gbps and 1.45 Gbps, respectively. The values reported herewith represent the highest data rate ever achieved in SLD (Table 3) and pave the way for future SLD-based SSL-VLC systems.
Fig. 4. Stand-alone SLD modulation bandwidth and data rate: (a) Modulation bandwidth response at different injection currents. (b) and (c) show the eye diagram for data rate of 1 Gbps, and 1.45 Gbps respectively.

Table 2. Data rates achieved with the SLD used for visible light communication (VLC).

| Data rate (Gbps) | CW Current (mA) | AC voltage before amplifier (mV) | BER            |
|------------------|-----------------|----------------------------------|----------------|
| 0.7              | 400             | 400                              | $2.0 \times 10^{-4}$ |
| 1                | 500             | 400                              | $1.7 \times 10^{-4}$ |
| 1.2              | 600             | 500                              | $6.0 \times 10^{-4}$ |
| 1.3              | 700             | 500                              | $1.1 \times 10^{-4}$ |
| 1.4              | 700             | 500                              | $1.9 \times 10^{-3}$ |
| 1.45             | 700             | 550                              | $1.8 \times 10^{-3}$ |

Table 3. Comparison of superluminescent diodes (SLD) used for visible light communications (VLC)

| $\lambda$ (nm) | Substrate material | Optical power | FWHM (nm) | Bandwidth, $f_{3\text{dB}}$ (MHz) | Data rate (Gbps) | Ref.   |
|----------------|--------------------|---------------|-----------|-----------------------------------|------------------|--------|
| 405            | Semipolar GaN      | 20 mW (CW)    | 9         | 807                               | 1.3              | [24]   |
| 447            | Semipolar GaN      | 123 mW (CW)   | 6.3       | 560                               | -                | [19]   |
| 442            | c-GaN              | 105 mW (CW)   | 6.5       | 405                               | 1.45             | This work |

4. Conclusions

In conclusion, we demonstrated VLC and SSL combined functionality visible-light device based on a c-plane GaN blue (442 nm) SLD with a broad FWHM of 6.5 nm and high-power output of 105 mW at 1 A of CW injection current. SLD-based warm white light with CCT of 3392 K and CRI of 85.1 were demonstrated along with a VLC record data rate of 1.45 Gbps using NRZ-OOK modulation scheme. Moreover, a record peak power of 474 mW was achieved under pulsed injection (2% duty cycle, 9.8 kHz). These results underscore the practicality of c-plane SLDs in realizing high-power, high data rate, speckle-free and droop-free SSL-VLC apparatus.
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