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Authors: Jorge A. Holguin-Lerma, Meiwei Kong, Omar Alkhazragi, Xiaobin Sun, Tien Khee Ng, Boon S. Ooi

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480-nm distributed-feedback InGaN laser diode for 10.5-Gbit/s visible-light communication

JORGE A. HOLGUIN-LERMA¹, MEIWEI KONG¹, OMAR ALKHAZRAGI, XIAOBIN SUN, TIEN KHEE NG, AND BOON S. OOI^{*}

Photonics Laboratory, King Abdullah University of Science and Technology (KAUST), Thuwal 23955-6900, Saudi Arabia

¹These authors contributed equally

^{*}Corresponding author: boon.ooi@kaust.edu.sa

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In this letter, we demonstrate a novel distributed-feedback (DFB) InGaN-based laser diode with narrow-linewidth emission at ~480 nm (sky blue) and its application to high-speed visible-light communication (VLC). A significant side-mode suppression ratio (SMSR) of 42.4 dB, an optical power of ~14 mW, and a resolution-limited linewidth of ~34 pm were obtained under continuous-wave operation. A 5-Gbit/s VLC link was realized using non-return-to-zero on-off keying (NRZ-OOK) modulation, whereas a high-speed 10.5-Gbit/s VLC data rate was achieved by using a spectral-efficient 16-quadrature-amplitude-modulation orthogonal frequency-division multiplexing (16-QAM-OFDM) scheme. The reported high-performance sky-blue DFB-laser is promising in enabling unexplored dense wavelength-division multiplexing (DWDM) schemes in VLC, narrow-line filtered systems, and other applications where single-frequency lasers are essential such as atomic clocks, high-resolution sensors, and spectroscopy. Single-frequency emitters at the sky-blue wavelength range will further benefit applications in the low-path-loss window of underwater media as well as those operating at the H-beta Fraunhofer line at ~486 nm. © 2019 Optical Society of America

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The recent advancement of the InGaN-based light-emitting diode, superluminescent diode, and laser diode (LD) has shown that novel device properties can be explored to satisfy emerging needs in the areas of illumination, optical communication, biomedical applications, and instrumentation [1–4]. Under this context, laser light with a narrow linewidth is attractive, as single wavelength emission between 400 nm to 550 nm is important for terrestrial and underwater applications, including visible-light communication (VLC), atomic clocks, and LIDAR sensing and surveying [5–7]. Particularly, VLC has emerged as a technology

that is capable of providing low-latency, covert, and large unlicensed bandwidth for complementing the fifth generation (5G) network and beyond [8,9]. A viable VLC system capable of multi-giga-bit-per-second (Gbit/s) poised to advance the VLC light-engine beyond laboratory proof-of-concept and meet the data capacity demand of a trunk line; a case in view would be to realize a high-power 10-Gbit/s data rate with an individual single-wavelength LD.

In order to achieve the single wavelength operation of InGaN LDs, various approaches have been investigated. These include external cavity optical elements and on-chip Bragg gratings, where the recent efforts on developing distributed feedback (DFB) gratings have made noteworthy progress. Different types of gratings have been reported, including buried grating [10], laterally-coupled and sidewall grating [11–13], as well as surface [14] and ridge-surface grating [15]. Here, we implemented an on-chip Bragg grating utilizing a focused ion beam (FIB) for the prototype demonstration of a beyond-10-Gbit/s LD incorporating a 40th-order DFB surface grating. A narrow linewidth emission at ~480 nm with a side-mode suppression ratio (SMSR) of up to 42.4 dB was achieved and thus confirming the effectiveness of our approach. A commercial sky-blue (~480 nm) InGaN-based LD, a wavelength that has not been explored in the LD-based VLC literature, was utilized. Merit arises at the sky-blue wavelength range due to its significance in underwater and low-background-noise applications, including those operated at the H-beta Fraunhofer line at ~486 nm [5].

The LD consists of an in-plane Fabry-Perot (FP) ridge waveguide [16] with a narrow ridge width of ~2 μm and a cavity length of ~605 μm. The design and fabrication of the DFB grating follows the Bragg condition given as [17]:

$$\Lambda = m \frac{\lambda}{2 n_{\text{eff}}}, \quad (1)$$

where Λ is the grating period, m is the order of the grating, λ is the operating wavelength in vacuum, and n_{eff} is the effective refractive index of the laser diode. A visual representation of the grating is shown in Fig. 1(a), where n_1 , n_2 and Λ_1 , Λ_2 represent the refractive

index and the size of each segment in a single grating period, respectively. The top-view image of the DFB-laser is shown in Fig. 1(b), and a schematic of the diffraction of light in the grating is shown in Fig. 1(c). The grating with $\Lambda = 3.88 \mu\text{m}$ and duty cycle of ~ 0.9 was fabricated using the FIB (FEI Helios NanoLab 650) with an accelerating voltage of 16 kV and an ion beam current of 0.13 nA for ~ 20 min. A total of 23 grooves were etched over a length of $\sim 85 \mu\text{m}$ at the back section of the laser diode, which has a high-reflection back-facet coating. An intentional phase-shift of $\pi/2$ is included in the first groove, which is closest to the back-facet [18].

The electro-optical device characterization was conducted under continuous wave (CW) operation using a Keithley 2520 system and a Labsphere integrating sphere incorporating a silicon photodetector. The device was actively cooled using a SaNoor-SN-LDM-T thermoelectric cooler (TEC) with a case temperature of 16°C . The laser linewidth, characterized as the full width at half maximum (FWHM), was measured using a high-resolution (>10 pm) optical spectrum analyzer (Yokogawa AQ6373B).

Fig. 1. (a) Schematic representation of a surface grating with >0.5 duty cycle (i.e., $\Lambda_1 > \Lambda_2$). (b) Top-view scanning electron micrograph of the $2\text{-}\mu\text{m}$ ridge waveguide, and the fabricated DFB surface grating with ~ 0.9 duty cycle. (c) Schematic of (b) illustrating the propagation (black arrow) and diffraction (dashed arrow) of light in the grating, where θ is the incidence or diffraction angle [17].

Fig. 2. Electro-optic characteristics under CW operation.

Figure 2 shows the light-output-current-voltage (L - I - V), the external quantum efficiency, and the current density characteristics of the fabricated DFB-laser. The device showed a lasing threshold at ~ 75 mA (~ 6.2 kA/cm ^{2}) and a turn-on voltage of ~ 4.3 V. The peak output power of ~ 14 mW was achieved at 150 mA (~ 12.4 kA/cm ^{2}) with a dV/dI series resistance (r_s) of $\sim 7.8 \Omega$.

The optical spectrum illustrated in Fig. 3 shows the DFB-LD emission centered at 479.712 nm with an FWHM of 34.5 pm and an SMSR of 42.4 dB. By using Equation (1), we calculated an effective refractive index (n_{eff}) of 2.4727 . Furthermore, the group effective index ($n_{\text{eff,g}}$) of this device, can be calculated from the cavity length (L) and the wavelength mode-spacing ($\Delta\lambda$) by [16]:

$$n_{\text{eff,g}} = \frac{\lambda^2}{2L\Delta\lambda}, \quad (2)$$

where we obtained $n_{\text{eff,g}} = 2.9716$, based on a $\Delta\lambda \sim 64$ pm, as measured from the spectrum in Fig. 3. The mode stability under different injection current was confirmed in Fig. 4(a). By changing the injected current from 90 mA up to 150 mA, a tuning coefficient of 6.25 pm/mA was observed, with a total peak wavelength change of 0.375 nm. Figure 4(b) shows the evolution of the linewidth and SMSR under the different injection currents.

Fig. 3. CW spectral emission of a sky-blue DFB-LD with a narrow linewidth at 479.712 nm, FWHM of 34.5 pm, and SMSR of 42.4 dB. Mode spacing of ~ 64 pm is indicated.

Fig. 4. (a) Spectral evolution of the sky-blue DFB-LD at different CW injection currents showing a tuning coefficient of 6.25 pm/mA. (b) FWHM and SMSR characteristics of the sky-blue DFB-LD under CW injection current.

Based on the electro-optical properties of the DFB-LD, we conducted direct device modulation for optical communication. The frequency response of the DFB-LD was measured using an Agilent E8361C PNA network analyzer, a Tektronix PSPL5580 bias-tee, an Alphasalas UPD-50-UP high-speed photodetector (PD),

and a variable neutral density (ND) filter at the receiver end. A calibration module Agilent E-Cal 85093-60010 was used to calibrate the response of the system. The bias-tee was used to mix the modulation signal and the direct current (DC) bias for operating the DFB-laser. The optical data was transmitted over a distance of ~ 38 cm in free space.

The results in Fig. 5 show that at the maximum current of 150 mA, the frequency response of the DFB-LD is relatively flat with a -10-dB bandwidth of ~ 2.6 GHz. The same setup was used to characterize an FP-LD from the same batch, i.e., without the fabrication of the DFB grating. The results in Fig. 6 show that under a similar output power of ~ 14 mW, the FP-LD has a -10-dB bandwidth of ~ 1.9 GHz. Under an equivalent injection current (i.e., same current density), the -10-dB bandwidth of the FP-LD is 2.2 GHz. Saturation of the PD was avoided by using the variable ND filter. The superior performance of the DFB-LD on the frequency response can be attributed to the self-locking mechanisms [19], showing that mode-locking methods are attractive for high-speed modulation. The -3-dB bandwidth of the DFB-LD (~ 1.1 GHz) and the FP-LD (~ 730 MHz at 150 mA and ~ 1.1 GHz at ~ 14 mW) in our measurements, are limited by sudden drops at ~ 1.1 GHz and ~ 1.6 GHz. These are found in both the DFB-LD and the FP-LD as seen in Fig. 5 and Fig. 6, indicating a signature of the system due to the components not used in the closed-loop calibration process, such as the circuit board of the laser mount enclosed in the TEC. In view of this, the effective -3-dB bandwidth of the DFB-LD could reach ~ 2.1 GHz, whereas the FP-LD would show a -3-dB bandwidth of ~ 730 MHz (at 150 mA) and ~ 1.5 GHz (at ~ 14 mW).

Fig. 5. Frequency response at different injection current of the sky-blue DFB-LD.

Fig. 6. Frequency response comparing the sky-blue DFB-LD and an FP-LD of the same batch at an equivalent optical power and injection current.

Given the modulation properties of the DFB-LD, its VLC capabilities were tested by using the non-return-to-zero on-off keying (NRZ-OOK) modulation scheme (Fig. 7). We used a pattern generator (Agilent N4903B J-BERT) to create a 1-V (peak-to-peak) signal having a pseudorandom binary sequence (PRBS) $2^{10}-1$ data stream, which was then transmitted using the DFB-LD and received at the PD. A digital communication analyzer (Agilent DCA-86100C) was used to capture the eye diagram of the VLC link (inset of Fig. 7).

Fig. 7. Achievable data rate with its corresponding BER in the NRZ-OOK VLC link. The trend curves show the speed limit of the 130-mA injection current, while being circumvented by increased injection currents. The inset shows the open eye diagram at 5 Gbit/s (150 mA) with a time scale of 200 ps/division.

Different data rates were characterized at different injection currents to study their influence in the maximum achievable data rate. At 130 mA, the data rate is limited by a sudden rise in the bit error ratio (BER) value, but this can be overcome by increasing the injection current. This is explained by the relation between an increased photon density and output power leading to a higher bandwidth in the frequency response [16]. A maximum data rate of 5-Gbit/s is achieved at 150 mA with a BER of 2.3×10^{-3} , which is below the forward error correction (FEC) limit of 3.8×10^{-3} .

To further improve the achievable data rate, spectral-efficient orthogonal frequency-division multiplexing (OFDM) [20] was adopted in the experiment. The parameters of the real-valued 16-quadrature amplitude modulation (QAM) OFDM signals are listed in Table 1.

Table 1. Main parameters of the OFDM signals

Parameter	Value
Data rate of the 16-QAM OFDM signals	10.5-Gbit/s
N ^o of subcarriers	108
Bit number of PRBS	$2^{20}-1$
Inverse fast Fourier transform size	1024
N ^o of cyclic prefix	10
N ^o of subcarriers for frequency gap near DC	3
N ^o of OFDM symbols (including two training symbols for synchronization and four training symbols for channel equalization)	154

The OFDM signals were uploaded into an arbitrary waveform generator (AWG, Tektronix AWG70002A). The output signals, sampled at a rate of 25 GSamples/s, with a peak-to-peak voltage of 500 mV were sent through an amplifier (Minicircuits ZHL-42W+)

and an attenuator (KT2.5-60/1S-2S), into the bias-tee. The optical signals were transmitted through a free space channel of ~ 38 cm and collected by the PD. The received signals were amplified and then captured by an oscilloscope (Tektronix DPO 72004C) using a sampling rate of 100 GSamples/s, followed by off-line processing on a computer. The experimental setup is shown in Fig. 8. The frequency response of the full system showed a -3-dB bandwidth of ~ 1.5 GHz and a -10-dB bandwidth of ~ 2.5 GHz.

A total frequency bandwidth of 2.637 GHz was utilized to transmit 10.5-Gbit/s OFDM signals. A mean BER of 2.708×10^{-3} was obtained with power-loading algorithm, where an allocated power of 5.13 dB was linearly emphasized on the subcarrier's indices from the 30th to the 108th. The corresponding well-converged constellation map and the BER per carrier are shown in Fig. 9.

Fig. 8. OFDM-VLC experimental setup: (a) the schematic and (b) experimental scene of the 16-QAM-OFDM-based VLC system. Inset shows the light from the ~ 480 -nm DFB-LD.

Fig. 9. The received OFDM signals at 10.5 Gbit/s: BER per subcarrier index with a mean value of 2.708×10^{-3} . Inset shows the constellation map of the received 16-QAM OFDM signals.

In conclusion, we demonstrated a sky-blue ~ 480 -nm InGaN-based DFB-LD under CW operation and its data transmission capabilities in VLC. A peak output power of ~ 14 mW was achieved along with an SMSR of up to 42.4 dB, a linewidth of ~ 34 pm, and mode stability of 6.25 pm/mA. The frequency response of the DFB-

LD-based VLC system offers an up-to-5-Gbit/s link using NRZ-OOK modulation and a 10.5-Gbit/s link using 16-QAM-OFDM scheme. The high-power, single-wavelength operation over multi-Gbit/s promises multi-channel communication based on closely adjacent wavelengths, mimicking the true wavelength-division multiplexing of the current optical-fiber communication system, by using optimally fewer devices and lower power. Ultimately, narrow-line sky-blue emitters may find niche application in underwater media and optical-background-filtered systems beyond the current demonstration.

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