4 Gbps direct modulation of 450 nm GaN laser for high-speed visible light communication

Changmin Lee,[1,*] Chong Zhang,[2] Michael Cantore,[1] Robert M. Farrell,[1,2] Sang Ho Oh,[2] Tal Margalith,[1] James S. Speck,[1] Shuji Nakamura,[1,2] John E. Bowers,[1,2] and Steven P. DenBaars[1,2]

[1]*Materials Department, University of California, Santa Barbara, California 93106, USA*
[2]*Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93117, USA*
[*]*changmin_lee@engineering.ucsb.edu*

Abstract: We demonstrate high-speed data transmission with a commercial high power GaN laser diode at 450 nm. 2.6 GHz bandwidth was achieved at an injection current of 500 mA using a high-speed visible light communication setup. Record high 4 Gbps free-space data transmission rate was achieved at room temperature.

OCIS codes: (060.2605) Free-space optical communication; (060.4080) Modulation; (140.7300) Visible lasers; (250.5960) Semiconductor lasers.

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1. Introduction

Solid-state lighting based on Gallium Nitride (GaN) by light emitting diodes (LEDs) has been developed as a highly efficient next generation lighting source and has been successfully commercialized in the market since the first blue LED was reported in 1993 [1, 2]. By taking advantage of existing solid-state white lighting based infrastructure, visible light communication (VLC) is available as a solution for dramatically increasing wireless data traffic currently constricted by the limited available spectrum of radio frequency (RF) communication [3]. Additional advantages further motivate VLC, such as the broad range of available THz frequencies in the unlicensed visible-light bandwidth, high security in operating area, and no interference with the current RF spectrum or other sensitive electronic equipment.

Great progress has been reported for high-speed data transmission using LEDs as a visible light transmitter. 400 MHz modulation bandwidth was demonstrated using a micro LED array to take advantage of a small chip resulting in a small RC time constant [4, 5]. However, due to its carrier lifetime limit (on the order of 1 ns), the data transmission rate of simple On-Off Keying (OOK) modulation is limited to 1.5 Gbit/s [6, 7]. Using orthogonal frequency-division multiplexing (OFDM), a transmission rate of 3 Gbit/s has been reported [8]. In white light communication, even if a blue filter is installed at the photo-detector to block the slow, yellow signal from the phosphor conversion with long photoluminescence phosphor lifetime (on the order of several μs), the resulting bandwidth is still low (~20 MHz) due to the reduced power from the filter and the inherent low bandwidth of the LED source [9]. Increasing the modulation bandwidth is necessary for further improvement in high data transmission rates in VLC systems.

Recent work in GaN laser diode based VLC showed significant improvement in the modulation bandwidth because the modulation speed of laser diodes is controlled by the photon lifetime (on the order of ps) instead of the carrier lifetime like LEDs. Recently, 1 GHz VLC system bandwidth of 450 nm laser diode has been demonstrated for the concept of RGB free space transmission [10]. A high-speed VLC using a 422 nm blue laser has been reported with a 1.4 GHz bandwidth and 2.5 Gbit/s of error free transmission [11]. This is almost three times larger than the record bandwidth of the blue LED-based VLC, even with the bandwidth of this system being limited by the response of the photo detector (PD) and, not the laser diode. Denault et al. demonstrated 442 nm laser based white lighting using YAG:Ce phosphor with a luminous efficacy of 76 lm/W [12]. As such, it should be possible to create a high-speed laser-based VLC that still leverages a white lighting system. Laser-based VLC will suffer less from the phosphor response than LED systems due to its higher power operation at high current density and larger inherent bandwidth than LEDs. However, the absence of high-speed PD in the blue spectral region has limited the measurement of bandwidth above the GHz level in the past [11]. This was not an issue in LED-based VLC systems because the bandwidth of LEDs was easily covered by available Si PDs. In this paper, we demonstrated the first high-speed VLC measurement limited by the bandwidth of 450 nm laser diode with a UV-extended high-speed PD. We specifically chose a UV-extended high-speed PD available for GHz level bandwidth measurement in blue range. The maximum bandwidth of the 450 nm laser diode was 2.6 GHz and data transmission rate was 4 Gbit/s with an open eye diagram. The modulation bandwidth using high-power laser diode shows how solid-state lighting can be compatible with communication.

2. Devices description and measurement setup

To measure the performance of the directly modulated blue laser, we set up a novel laser-based free space transmission VLC. The 450 nm laser diode was extracted from a Casio XJ-M140 projector. The laser diode, had a cavity length of 1150 μm, ridge width of 15 μm, and a 10 μm current aperture, as shown in Fig. 1(a). Continuous wave (CW) operation of this wide

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ridge laser is necessary for direct modulation. The light-current-voltage (LIV) characteristics and spectrum were measured to determine the large signal properties of the laser diode. For the frequency response measurement shown in Fig. 1(b), a sinusoidal signal with small RF power (0 dBm ~10 dBm) generated by an RF signal generator (R&S SMF100A) was directly modulated on top of a DC bias baseline using a bias tee (Mini-Circuit ZFBT - 6GW). The signal of the CW laser diode was transmitted to a high-speed silicon photodiode with a 0.13~0.14 A/W responsivity at 450 nm (ALPHALAS UPD-50-UP). The light output from laser diode traversed about 15 cm of free space and then was collected into the photo detector via a 0.25 NA lens. The received signal was measured by a digital component analyzer (DCA, Agilent 86100C) at different drive currents. To determine the high data rate characteristics of the blue laser diode, a pseudo-random bit sequence (PRBS) from a pattern generator (Anritsu MP1763C) was added at each DC operating bias and eye diagrams were measured by the DCA as depicted in Fig. 1(c).

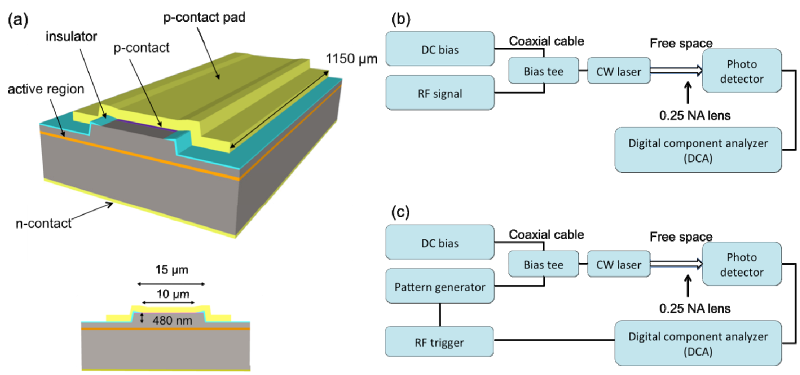

Fig. 1. (a) Illustration of the edge emitting laser design. (b) Schematic block diagram of the VLC setup for determining frequency response. (c) Diagram of the data transmission testing setup.

Table 1 shows the bandwidth limit of each component in the measurement system. It was expected that the laser diode would limit the bandwidth of the measurement system, below the 6 GHz limit of the bias tee. The laser diode was mounted in a TO5 package surrounded by a large aluminum heat sink. Thus, experiments were performed at room temperature without a temperature controller.

Table 1. Bandwidth limits of VLC components

Component	Bandwidth limit (GHz)
RF generator	40
Pattern generator	12.5
Bias tee	6
Photo detector	7
Digital component analyzer	80

3. Experimental results and discussion

LIV characteristic curves for the laser are shown in Fig. 2(a). Since the PD was set up 15 cm away from the laser diode, actual output power of the laser is higher than the measured data when placed in front of the PD. The threshold current of the laser was 170 mA and the threshold current density was 1.48 kA/cm^2, with a threshold voltage of 4 V. Figure 2(b) shows, the optical spectrum measured at each drive current. The wavelength only shifted 1~2

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nm around 450 nm for drive currents ranging from 180 mA to 600 mA, the same drive currents points used in the frequency response test.

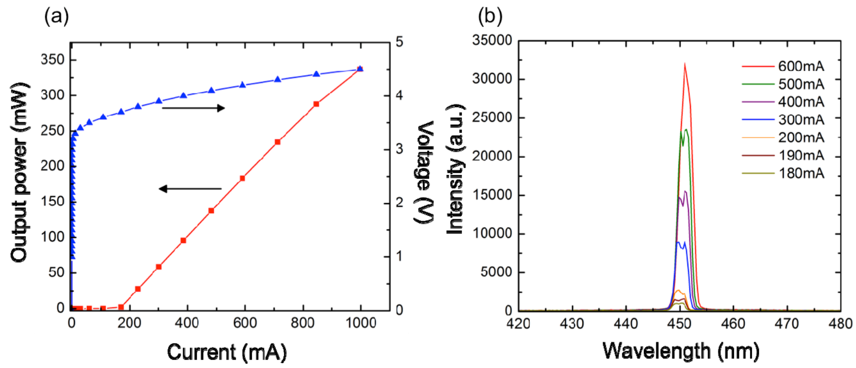

Fig. 2. (a) LIV characteristics and (b) optical spectra of the 450 nm laser diode at room temperature.

Sinusoidal RF signals were applied to the biased laser diode by a RF signal generator and measured by the DCA to study the high-speed characteristics of the frequency response of the 450 nm ridge laser. The magnitude of the frequency response was calculated by dividing the output amplitude obtained at the PD by the reference noise level at the PD in the frequency domain. The measured data is shown in Fig. 3 with a 6th order polynomial curve fit to the data points. Each data point was collected at 20 MHz increments below 1 GHz and 50MHz increments above 1 GHz with 1 min pauses between each measurement for cooling down the laser. Each curve corresponds to the individual drive current from 180mA, which is right above threshold, up to 600 mA, which is where the bandwidth stops increasing. The measured maximum −3 dB bandwidth is 2.6 GHz at a drive current of 500 mA. The 2.6 GHz limit is attributed to the modulation bandwidth of the laser diode since the other components of the VLC system have more bandwidth than the 6 GHz bandwidth of the bias tee. This −3 dB bandwidth is determined by the relaxation resonance frequency (f_R) roll-off past the peak resonance.

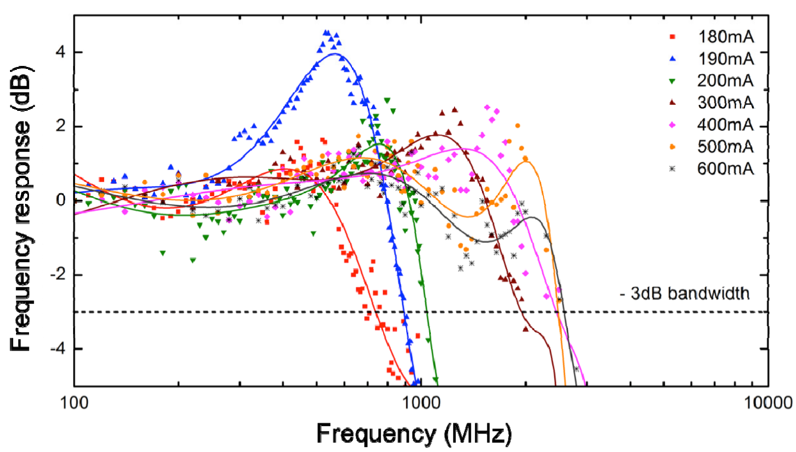

Fig. 3. Small signal frequency response of the laser diode in the VLC system at varying drive currents. The symbols are measured data points and the solid curves are a 6th-order polynomial approximation fit to the data.

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From the two parameter modulation transfer function (small signal photon density/small ac current) of the laser given by Eq. (1) [13], damping characteristics – are described by the relaxation resonance frequency, ω_r, and the damping factor, γ. At small bias current, the frequency response is in an under-damped regime and has a high and narrow peak near ω_r. As the drive current increases, the bandwidth finally reaches the maximum at the critical damping regime around 400 mA ~600 mA. At higher drive currents, the bandwidth starts to be limited by damping, rolling off gradually from a broad and small peak [13]. This corresponds to 2.6 GHz near 600 mA, similar to the maximum value at 500 mA.

$$\left|H(\omega)\right| = \frac{\omega_r^{\,2}}{\sqrt{(\omega_r^{\,2}-\omega^2)^2+\gamma^2\omega^2}} \tag{1}$$

$$f_R = \frac{1}{2\pi}\left[\frac{\Gamma v_g a}{qV}\eta_i (I - I_{th})\right]^{1/2} \tag{2}$$

From the equation for relaxation resonance frequency Eq. (2), the square root of the driving current above the threshold is linearly proportional to the relaxation oscillation frequency (f_R) [13,14] because the current term is approximately proportional to the photon density, where Γ is the confinement factor, v_g is the group velocity, a is the differential gain, V is the active region volume, η_i is the injection efficiency, and I_{th} is the threshold current. This is shown in Fig. 4(a). The slope value, 0.11 GHz/mA$^{1/2}$, represents the properties of the laser relative to the frequency characteristics. The −3 dB bandwidth is eventually limited near the critical damping of 2.6 GHz, as shown in Fig. 4(b). Since the frequency response has a resonance, the large capacitance originating from the large cavity is not limiting factor. The measured capacitance is 25.5 pF with 1.22 Ω of series resistance at 500 mA, and consequently, the RC limited modulation bandwidth is 5.12 GHz. Thus, the bandwidth saturation is due to either heating of the active region, causing a reduction in differential gain, or spectral hole burning.

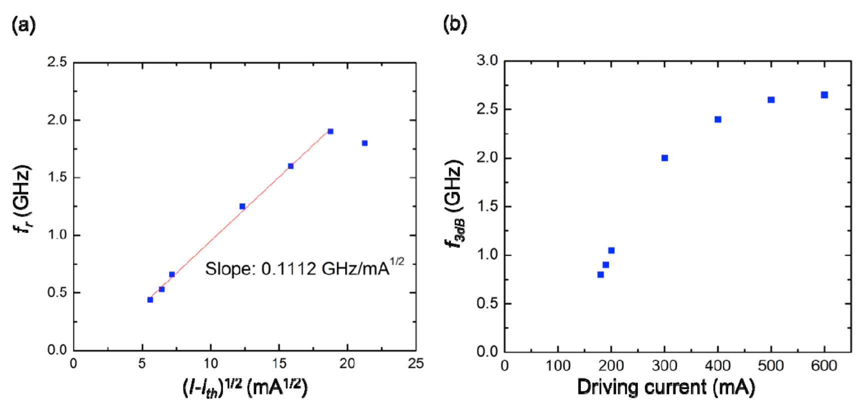

Fig. 4. (a) The dependence of relaxation resonance frequency on the drive current and (b) the dependence of the −3 dB bandwidth limit on the drive current.

The measurement of the data transmission rate was performed with 2^7-1 non-return-to-zero (NRZ) PRBS for communication testing. For the highest data rate performance, the patterns were biased at a DC drive current of 500 mA having the maximum modulation frequency of 2.6 GHz. As shown in Fig. 5, peak-to-peak 2 V of output data signal is applied and the maximum data rate for the open eye diagram was 4 Gbit/s. The measured extinction ratios were 0.950 dB and 0.735 dB for 2 Gbit/s and 4 Gbit/s, respectively. The Q-factors were calculated to be 12.06 dB and 10.78 dB for 2 Gbit/s and 4 Gbit/s, respectively, using Eq. (3),

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where $I_{1,2}$ is the photo-current at the state 0 and 1, $\sigma_{1,2}$ is the noise variance at 0 and 1, Q is the quality factor, and BER is the bit error rate. Also, BER were 3.06×10^{-5} bits and 2.70×10^{-4} bits for 2 Gbit/s and 4Gbit/s, respectively, as calculated using Eq. (4). This BER is mainly outcome of the high loss in free space path as well as the low PD responsivity.

$$Q = \frac{I_1 - I_0}{\sigma_1 - \sigma_0} \tag{3}$$

$$BER \approx erfc\left[\frac{Q}{\sqrt{2}}\right] \tag{4}$$

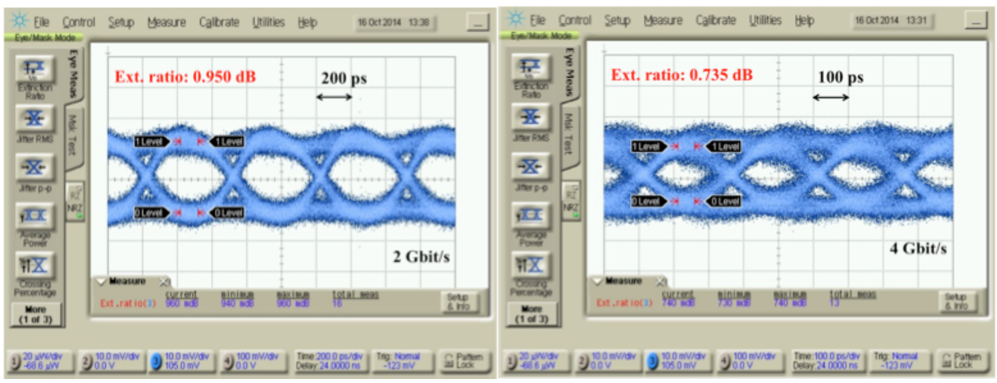

Fig. 5. Eye diagrams of the digital modulation with 2 Gbit/s (left) and 4 Gbit/s (right).

4. Summary

A novel optical transmission system for wireless communication has been demonstrated using a 450 nm GaN ridge laser diode. The results show that high frequency and high-speed data transmission performance were limited by the bandwidth of the laser diode. The bandwidth of 2.6 GHz and a 4 Gbit/s data transmission rate by direct NRZ OOK modulation demonstrates the great potential for high power lasers in visible light communication, overcoming the intrinsic limitations of LEDs. Further work on this system will be done with phosphor converted blue light and short pass filters for white light communication.

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