2 Gbit/s data transmission from an unfiltered laser-based phosphor-converted white lighting communication system

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Abstract: We demonstrate data transmission of unfiltered white light generated by direct modulation of a blue gallium nitride (GaN) laser diode (LD) exciting YAG:Ce phosphors. 1.1 GHz of modulation bandwidth was measured without a limitation from the slow 3.8 MHz phosphor response. A high data transmission rate of 2 Gbit/s was achieved without an optical blue filter using a non-return-to-zero on-off keying (NRZ-OOK) modulation scheme. The measured bit error rate (BER) was less than the forward error correction (FEC) limit of $3.50 \times 10^{-3}$. The generated white light exhibits CIE 1931 chromaticity coordinates of (0.3628, 0.4310) with a color rendering index (CRI) of 58 and a correlated color temperature (CCT) of 4740 K when the LD was operated at 300 mA. The demonstrated laser-based lighting system can be used simultaneously for indoor broadband access and illumination applications with good color stability.

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References and links


1. Introduction

Since gallium nitride (GaN)-based blue light emitting diodes (LEDs) were first developed in 1993, there has been significant improvements to commercialize them in many applications such as displays, traffic signs, and solid-state white lighting [1–4]. In addition to lighting applications, in recent years visible light communication (VLC) has emerged as a new application as data-rate demands are exponentially growing due to increasing mobile use, exceeding the capacity existing radio frequency (RF) spectrum in the near future [5,6]. VLC has gained more momentum with further advantages: 1) hundreds THz of available unlicensed spectrum; 2) no electromagnetic interference (EMI); 3) highly secured data transmission; and 4) cost-efficient communication.

Most of the research on VLC has been based on LEDs. However, high-speed modulation of phosphor-based LED white light sources has been hindered by the long relaxation time of
the phosphor or large RC parasitics [7], limiting the transmission capacity of the VLC. There are a number of methods, such as blue filtering, pre-equalization, and post-equalization reported to enhance the bandwidths and data rates of VLC systems [8–10]. Very recently, a data rate of 1 Gbit/s with improved modulation bandwidth was reported by using an LED with an unconventional phosphor with a short relaxation lifetime (100 of ps) to produce yellowish white emission [11]. In order to increase the LED modulation bandwidth limited by RC parasitics, micro LED arrays have been used to achieve data rates up to 500 Mbit/s using a non-return-to-zero on-off keying (NRZ-OOK) modulation [7,12,13]. To improve the data transmission, 3 Gbit/s of higher order modulation has been performed using orthogonal frequency-division multiplexing (OFDM) with a single micro LED [14]. However, the micro LED design needs more improvement for practical solid-state lighting due to its low power and potentially issues with pixel-control. Furthermore, LEDs suffer a loss in external quantum efficiency (EQE) as operating current increases, commonly known as “efficiency droop” [15–19].

In contrast to LEDs, laser diodes (LDs) do not exhibit efficiency droop above threshold. The output power and external quantum efficiency (EQE) of LDs increase monotonically with input current. Recent studies with LDs as a light engine showed high potential for solid-state lighting as well as VLC. Laser-based white lighting is emerging as a candidate of next generation white lighting with reported efficacy of 76 lm/W [19–21]. For optical communication, a reported 2.6 GHz modulation bandwidth in commercial high-power LD shows that LDs can be modulated at least 100 times higher than LEDs [22]. High-speed blue LDs can potentially be suitable for plastic optical fibers (POFs) based low-speed and short-distance communications [23]. In addition to the modulation speed, a narrow emission spectrum of 2–3 nm allows wavelength-division multiplexing (WDM) as well as OFDM in red-green-blue (RGB) lasers for white light communication [24,25].

In our study, we demonstrated 2 Gbit/s data transmission from unfiltered white light generated by direct modulation of a blue GaN laser diode exciting YAG:Ce phosphors. The effect of phosphors on the modulation characteristic was investigated, and we observed that the modulation bandwidth was not limited by the phosphor. The measured bit error rate (BER) was $3.50 \times 10^{-3}$ at 2 Gbit/s data transmission rate without the blue filter, which is below the forward error correction (FEC) threshold required for error-free operation. In addition, the laser-based white lighting system showed a correlated color temperature (CCT) value of 4740 K at 300 mA, similar to the CCT of daylight. Our result shows that using blue GaN laser diodes to excite YAG:Ce phosphors is an effective and cost-efficient solution for next-generation high data rate VLC systems without the need for RGB lasers or an additional optical filter.
2. Device properties and experimental description

Fig. 1. (a) 450 nm GaN laser diode mounted on thermo-electric cooler (TEC) and heat sink. (b) LIV characteristic curves by front-end measurement.

The high power edge emitting 450 nm GaN LD reported in this paper was extracted and re-packaged from a Casio XJ-M140 projector. As shown in Fig. 1(a), the packaged LD was mounted on a thermoelectric cooler (TEC) module with temperature controller included. The interface between the circular LD module and TEC was filled with copper foil to avoid an air gap in the thermal path. The SubMiniature version A (SMA) connector was directly soldered to the leads from the LD module to minimize impedance mismatch. Light-current-voltage (LIV) characteristics were measured from facet of the LD under continuous wave (CW) operation, and are shown in Fig. 1(b). The threshold current was around 140 mA with a corresponding threshold voltage of 3.8 V at 16 ºC. Unlike LEDs, which suffer from efficiency droop at high current densities, the differential efficiency in LDs is constant at high current densities because the carrier density clamps above threshold. Further details about the device structure can be found in Lee et al [18].

Fig. 2. (a) Schematic diagram of white light communication setup for direct OOK modulation. (b) Photograph of YAG:Ce single crystal phosphor (SCP). (c) Photograph of the experimental setup.
Fig. 2. shows the experimental setup of laser-based white light VLC data transmission and illumination system using phosphor conversion. The input signal from the bit error rate tester (BERT, Agilent N4903B J-BERT) was pre-amplified using a 12.5 Gbit/s driver amplifier (Picosecond 5865) and then jointed with a DC bias using a bias-tee before being feed into the LD. The light output was collimated through the transmitter (Tx) lens (Thorlabs LA1145-A) followed by a variable attenuator for controlling the intensity level. The blue laser light was then used to excite a cylindrical single crystal cerium-doped Yttrium aluminum garnet (YAG:Ce) phosphor plate. The light was then passed through a commercially available 80 µm thick polyethylene terephthalate (PET) plastic diffuser film to generate uniform white emission. The single crystal YAG:Ce phosphor was thinned to 700 µm to make the combined laser-phosphor emission spectrum white. The modulated white light travelled 5 cm from phosphor conversion where it was received by a 1 GHz Si avalanche photodetector (APD, Menlo Systems APD 210) with three receiver (Rx) lenses in series (Thorlabs LA 1145-A, LA1401, and LA1145). The eye diagrams and BERs of received signals were measured by a digital communications analyzer (DCA, Agilent 86100) and BERT. The VLC system bandwidth was limited by APD having a cut-off bandwidth of 1 GHz. However, this issue can be mitigated via using a faster photodetector (PD) as demonstrated by Lee et al [18].

3. Experimental results and discussion

![Fig. 3.](image)

Fig. 3. (a) CIE chromaticity coordinates, (b) Optical spectra, and (c) luminous flux and luminous efficacy of laser-based white lighting system. (d) Time resolved photoluminescence lifetime of single crystal YAG:Ce with exponential fitting.

The properties of white light emission were investigated as shown in Fig. 3. The measurements were performed using a GL Spectis 5.0 Touch spectrometer with an integrating
sphere. As shown in Fig. 3(a), the white emission from the LD combined with the single crystal phosphor (SCP) had Commission Internationale de l’Eclairage (CIE) 1931 x,y chromaticity coordinates (0.3628, 0.4310) with a color rendering index (CRI) of 58 and a CCT of 4740 K at 300 mA of drive current. CRI and CCT show little variation with drive current between 200 mA and 400 mA with CRI change of ± 0.1 and CCT change of ± 10K. The ratio of unconverted to converted photons observed in the SCP-LD combined emission is determined by the amount of laser emission absorbed by the single crystal phosphor. At normal incidence this ratio is minimized with the shortest optical path through the phosphor of 700 µm, but can be increased by increasing the incidence angle. The CIE coordinates can be moved near the Planckian locus with further optimization of phosphor thickness and mounting angle. The choice of single crystal phosphor rather than conventional powder based phosphor is due to thermal degradation of typical phosphor-in-matrix composites which occurs at high laser power intensity. The spectra of the laser-based white lighting system with different drive currents are presented in Fig. 3(b). This data was used to calculate the luminous flux and efficacy of the system, which are plotted in Fig. 3(c). The luminous flux increases linearly above the threshold current up to 61.5 lm at 400 mA, following the trend of the laser output power. The increase of luminous efficacy begins to saturate at 400 mA due to the thermal effects, showing a peak value of 37.2 lm/W. The relaxation time of single crystal YAG:Ce was investigated by time-resolved photoluminescence lifetime (TRPL) measurement as shown in Fig. 3(d). By using \( y = A \exp(-x/\tau) + y_0 \) as a fitting equation, ~73 ns of relaxation time (\( \tau \)) was obtained for the single crystal phosphor. The 3 dB bandwidth can be calculated by the power transfer function as [26]:

\[
H^2_{PL}(\omega) = \frac{1}{1+j\omega\tau}
\]

(1)

\[
f_{3dB} = \frac{\sqrt{3}}{2\pi\tau}
\]

(2)

The half of absolute power transfer function (\( |H^2_{PL}(\omega)| \)) corresponding to the value at ~3 dB frequency of single crystal YAG:Ce phosphor is ~3.8 MHz, which is the expected order of frequency.

Fig. 4. Measured small signal frequency response of (a) blue laser emission only, (b) phosphor-converted white emission, and (c) white emission with blue filter installed in front of the APD to filter out the phosphor-converted yellow components.

Small signal response measurement was performed under different drive currents using a network analyzer (Agilent E8361C PNA) in three scenarios: (a) only blue laser emission, (b) phosphor converted white emission, and (c) white emission with blue filter installed in front of the APD to filter out the phosphor converted yellow components, as shown in Fig. 4. The obtained highest ~3 dB bandwidths for the three scenarios were 1.2 GHz, 1.1 GHz, and 1.2 GHz, respectively. All three modulation bandwidths are approximately 1 GHz, which was
limited by the APD. The increase in normalized response above 1 GHz in 400 mA of the drive current in Fig. 4(a), and (c) is most likely related to APD noise. Since the photons are scattered in the phosphor conversion process, a reduction of received power will cause a lower SNR, resulting in slight reduction of bandwidth. In addition, since the yellow component has a 3.8 MHz bandwidth, which is almost three orders of magnitude lower than that of the blue component, it has a negligible effect on the normalized response. Even though the system bandwidth is limited to 1 GHz, it is important to note that the modulation bandwidth of the phosphor-converted white light is not limited by the bandwidth of the phosphor components, which is on the order of several MHz.

![Diagram of normalized response vs. frequency for LEDs and Lasers](image)

Fig. 5. Comparison of the modulation bandwidth of commercial blue LEDs and blue LDs with and without phosphor conversion.

Fig. 5. shows the modulation bandwidths of commercial blue LEDs (Luxeon STAR) and blue LDs (extracted from Casio XJ-M140 projector) with and without phosphor-conversion. The operating current of the LED was 200 mA and the operating current of the LD was 300 mA. The reported bandwidth of the LED with and without phosphor conversion with a blue filter in front of the PD was only 2.5 MHz and 14 MHz, respectively [22]. The bandwidth of LEDs with phosphor conversion is limited by the phosphor lifetime (on the order of 100 ns). In contrast, the bandwidth of LDs with phosphor conversion is not limited by the phosphor lifetime. The bandwidth of LDs depends on photon lifetime (on the order of 10 ps), while the bandwidth of LEDs depends on radiative recombination lifetime (on the order of 1 ns), so the modulation bandwidth of LDs can be at least 100 times higher than LEDs [22]. For LEDs with phosphor conversion, the decay time of the radiative recombination is of the same order as the decay of phosphor and the emission has similar intensity, so the total frequency response is highly affected by the frequency response of the phosphor. For a LD, since the relaxation time is approximately two orders of magnitude lower, the modulation at high frequency is dominated by the photon lifetime of the LD. The lifetime of a system consisting of a LD with phosphor conversion can be calculated by

$$\frac{1}{\tau_{\text{total}}} = \frac{1}{\tau_{\text{LD}}} + \frac{1}{\tau_{\text{P}}}$$  \hspace{1cm} (3)$$

where \(\tau_{\text{total}}\), \(\tau_{\text{LD}}\), and \(\tau_{\text{P}}\) are the total lifetime of the LD/phosphor combination, the individual LD lifetime, and the individual phosphor lifetime, respectively. With at least two orders of
magnitude difference between the lifetimes, \( \tau_p \) is negligible, resulting in a bandwidth that is not affected by the phosphor lifetime (\( \tau_{\text{total}} \approx \tau_{\text{LD}} \)). Thus, our laser-based phosphor-converted white VLC system does not require an optical blue filter or a post-equalization circuit, which is necessary to recover the bandwidth compromised by the phosphor in LED-based phosphor-converted white VLC systems [8–10].

The data transmission measurement was performed at a drive current of 300 mA by a 2\(^{10}\)-1 pseudo-random binary sequence (PRBS) for BER and an eye test. As shown in Fig. 6, unfiltered white emission passed FEC criteria with a BER of 3.50 \times 10^{-3} at 2 Gbit/s while the signals after blue filter had a BER of 6.20 \times 10^{-3} at 2 Gbit/s. Open eyes were obtained at 1 Gbit/s and 2 Gbit/s without significant difference between the scenarios of filtered and unfiltered receiver (see Fig. 6(c) and (d)), with measured SNR of 5.5 and 2.7, respectively. Unlike LED-based white light communication, the measured data transmission shows that a blue filter is not necessary to improve the data transmission rate for laser-based white light communication [7, 8].

4. Conclusion

In our study, we demonstrate 2 Gbit/s data transmission from an unfiltered laser-based phosphor-converted white lighting system. The unfiltered white light was generated by exciting YAG:Ce phosphors with a directly modulated blue GaN laser diode. A phosphor-converted white lighting communication system has been demonstrated by using a blue LD and a single crystal YAG:Ce phosphor. The modulation bandwidth was measured in three scenarios: (1) blue laser emission, (2) phosphor-converted white emission, and (3) white emission with blue filter installed in front of the APD to filter out the phosphor-converted yellow components. The bandwidths in all three cases were 1.1–1.2 GHz and were limited by the APD. 2 Gbit/s data transmission by direct OOK modulation was demonstrated. Corresponding open eye diagrams and a FEC compliant BER of 3.50 \times 10^{-3} were achieved. In addition, white light characteristics measurements revealed a CRI of 58 and a CCT of 4740 K, which is comparable to the CCT of daylight. These results show the potential of laser-based
phosphor-converted white lighting systems for high data rate VLC without the need for an optical blue filter.

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