Going beyond 4 Gbps data rate by employing RGB laser diodes for visible light communication

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Abstract: With increasing interest in visible light communication, the laser diode (LD) provides an attractive alternative, with higher efficiency, shorter linewidth and larger bandwidth for high-speed visible light communication (VLC). Previously, more than 3 Gbps data rate was demonstrated using LED. By using LDs and spectral-efficient orthogonal frequency division multiplexing encoding scheme, significantly higher data rates has been achieved in this work. Using 16-QAM modulation scheme, in conjunction with red, blue and green LDs, data rates of 4.4 Gbps, 4 Gbps and 4 Gbps, with the corresponding BER/SNR/EVM of 3.3×10^{-3}/15.3/17.9, 1.4×10^{-3}/16.3/15.4 and 2.8×10^{-3}/15.5/16.7were obtained over transmission distance of ~20 cm. We also simultaneously demonstrated white light emission using red, blue and green LDs, after passing through a commercially available diffuser element. Our work highlighted that a tradeoff exists in operating the blue LDs at optimum bias condition while maintaining good color temperature. The best results were obtained when encoding red LDs which gave both the strongest received signal amplitude and white light with CCT value of 5835K.

OCIS codes: (060.4510) Optical communications; (060.4250) Networks; (140.2020) Diode lasers; (140.7300) Visible lasers; (060.2630) Frequency modulation; (060.2605) Free-space optical communication.

References and links

1. J. Vucic, C. Kottke, S. Nerreter, K. Habel, A. Buttner, K. D. Langer, and J. W. Walewski, “230 Mbit/s via a wireless visible-light link based on OOK modulation of phosphorescent white LEDs,” in Optical Fiber Communicaiton and Collocated National Fiber Optic Engineers Conference, 2010, paper ThH3.
2. C. H. Yeh, Y. F. Liu, C. W. Chow, Y. Liu, P. Y. Huang, and H. K. Tsang, “Investigation of 4-ASK modulation with digital filtering to increase 20 times of direct modulation speed of white-light LED visible light communication system,” Opt. Express **20**(15), 16218–16223 (2012).
3. D. O’Brien, H. Le Minh, L. Zeng, G. Faulkner, K. Lee, D. Jung, Y. J. Oh, and E. T. Won, “Indoor visible light communications: challenges and prospects,” Proc. SPIE **7091**, 709106 (2008).
4. H. Elgala, R. Mesleh, and H. Haas, “Indoor optical wireless communication: potential and state-of-the-art,” IEEE Commun. Mag. **49**(9), 56–62 (2011).
5. L. Hanzo, H. Haas, S. Imre, D. O’Brien, M. Rupp, and L. Gyongyosi, “Wireless myths, realities, and futures: From 3G/4G to optical and quantum wireless,” Proc. IEEE **100**, 1853–1888 (2012).
6. C. W. Chow, C. H. Yeh, Y. F. Liu, and Y. Liu, “Improved modulation speed of LED visible light communication system integrated to main electricity network,” Electron. Lett. **47**(15), 867–868 (2011).
7. A. M. Khalid, G. Cossu, R. Corsini, P. Choudhury, and E. Ciaramella, “1-Gb/s transmission over a phosphorescent white LED by using rate-adaptive discrete multitone modulation,” IEEE Photonics J. **4**(5), 1465–1473 (2012).
8. C. H. Yeh, Y. L. Liu, and C. W. Chow, “Real-time white-light phosphor-LED visible light communication (VLC) with compact size,” Opt. Express **21**(22), 26192–26197 (2013).

#240960 Received 18 May 2015; revised 25 Jun 2015; accepted 27 Jun 2015; published 10 Jul 2015

9. F. M. Wu, C. T. Lin, C. C. Wei, C. W. Chen, Z. Y. Chen, and H. T. Huang, "3.22-Gb/s WDM visible light communication of a single RGB LED employing carrier-less amplitude and phase modulation," in Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (2013).
10. G. Cossu, A. M. Khalid, P. Choudhury, R. Corsini, and E. Ciaramella, "3.4 Gbit/s visible optical wireless transmission based on RGB LED," Opt. Express **20**(26), B501–B506 (2012).
11. J. Grubor, S. Randel, K. D. Langer, and J. W. Walewski, "Bandwidth-efficient indoor optical wireless communications with white light-emitting diodes," Csndsp 08: Proceedings of the Sixth International Symposium on Communication Systems, Networks and Digital Signal Processing, 165–169 (2008).
12. W. Y. Lin, C. Y. Chen, H. H. Lu, C. H. Chang, Y. P. Lin, H. C. Lin, and H. W. Wu, "10m/500Mbps WDM visible light communication systems," Opt. Express **20**, 9919-9924 (2012).
13. D. Tsonev, H. Chun, S. Rajbhandari, J. J. D. McKendry, S. Videv, E. Gu, M. Haji, S. Watson, A. E. Kelly, G. Faulkner, M. D. Dawson, H. Haas, and D. O'Brien, "A 3-Gb/s single-LED OFDM-based wireless VLC link using a gallium nitride μLED," IEEE Photonics Technol. Lett. **26**(7), 637–640 (2014).
14. J. Piprek, "Efficiency droop in nitride-based light-emitting diodes," Phys. Status Solidi a-Applications and Materials Science **207**(10), 2217–2225 (2010).
15. H. Le Minh, D. O'Brien, G. Faulkner, O. Bouchet, M. Wolf, L. Grobe, and J. Li, "A 1.25-Gb/s indoor cellular optical wireless communications demonstrator," IEEE Photonics Technol. Lett. **22**(21), 1598–1600 (2010).
16. S. Watson, M. Tan, S. P. Najda, P. Perlin, M. Leszczynski, G. Targowski, S. Grzanka, and A. E. Kelly, "Visible light communications using a directly modulated 422 nm GaN laser diode," Opt. Lett. **38**(19), 3792–3794 (2013).
17. Y. C. Chi, D. H. Hsieh, C. T. Tsai, H. Y. Chen, H. C. Kuo, and G.-R. Lin, "450-nm GaN laser diode enables high-speed visible light communication with 9-Gbps QAM-OFDM," Opt. Express **23**(10), 13051–13059 (2015).
18. A. Neumann, J. J. Wierer, Jr., W. Davis, Y. Ohno, S. R. J. Brueck, and J. Y. Tsao, "Four-color laser white illuminant demonstrating high color-rendering quality," Opt. Express **19**(S4 Suppl 4), A982–A990 (2011).
19. D. Tsonev, S. Videv, and H. Haas, "Towards a 100 Gb/s visible light wireless access network," Opt. Express **23**(2), 1627–1637 (2015).
20. M.-C. Cheng, Y.-C. Chi, Y.-C. Li, C.-T. Tsai, and G.-R. Lin, "Suppressing the relaxation oscillation noise of injection-locked WRC-FPLD for directly modulated OFDM transmission," Opt. Express **22**(13), 15724–15736 (2014).
21. S. Forestier, P. Bouysse, R. Quere, A. Mallet, J.-M. Nebus, and L. Lapierre, "Joint optimization of the power-added efficiency and the error-vector measurement of 20-GHz pHEMT amplifier through a new dynamic bias-control method," IEEE Trans. Microw. Theory Tech. **52**(4), 1132–1141 (2004).

1. Introduction

In the last few years, the usage of light-emitting devices (LEDs) for lighting application has gained popularity. LED-based solid-state technology shows reliability, stability, low power consumption, low cost and easy controllability. In view of its potential wide spread application, new exploration for using these light source for simultaneous optical wireless communication (OWC) has been explored [1, 2]. With tremendous increase in data throughput, wireless communication based on radio frequency (RF)is becoming the backbone of data transfer for indoor and outdoor environment [3, 4]. Alternative electromagnetic spectrum, such as millimeter wave, terahertz and optical waves, have to be considered to take off the load from the conventional low frequency based communications [5]. With expensive components requirement for high frequency based data transfer, OWC, which rely on a diverse option of high speed, off-the-shelf, high bandwidth components is the most feasible option. The utilization of various modulation schemes based on intensity and direct detection make OWC implementation straight forward. Furthermore, OWC provides an unregulated bandwidth with no interference with sensitive electronic instruments, thus allowing possible integration with the existing infrastructure [6].

Up until now, considerable work has been done in OWC utilizing LEDs. A step forward in OWC is to realize white light generation in conjunction with data communication. Two competing technologies have emerged in achieving this goal. The first one employs blue LED to excite yellow phosphor, which in turn emits a broad spectrum [7, 8]. The second approach makes use of red, green and blue (RGB) LEDs, which are mixed to generate white light [9, 10]. The technique utilizing phosphor is easier and cheaper to implement, but suffers from long carrier lifetime that considerably limits the modulation bandwidth to several MHz. With a band pass filter to remove the slower components of the emitted broad spectrum, bandwidth up to few tens of MHz has been achieved [11]. In the RGB LEDs approach, the intensity ratio

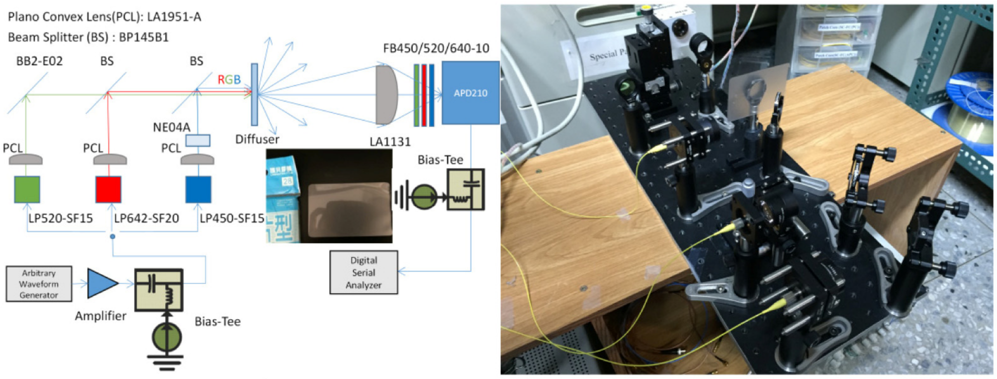
#240960 Received 18 May 2015; revised 25 Jun 2015; accepted 27 Jun 2015; published 10 Jul 2015

of the LEDs can be tuned for better control over the white light characteristics, such as correlated color temperature (CCT).In addition to that, wavelength division multiplexing (WDM) can be employed to send data on parallel and independent data streams thus further increasing the data rate [12]. Alternatively, complex signal processing techniques such as signal equalization, adaptive bit loading, and orthogonal frequency division multiplexing (OFDM) can serve to more efficiently utilize the channel, boosting the data rate up to 3.4Gbps [10, 13].

Though LED-based lighting has shown luminous efficacy levels above 200 lm/watt, their operation is still limited to lower injection current levels. Design based on micro-LEDs have shown improvement in larger injected current densities and low capacitance but they still suffer from the universally accepted "efficiency droop" problem [13, 14]. This provides the motivation to use laser diodes (LDs), having the highest electrical to optical conversion efficiency with no droop issue, as the suitable candidate for front-end transmitters. In addition, LD wavelength profile is in the order of <3nmthat is ideal for WDM, which allows multiple parallel channels to carry data thus considerably increasing the data rates.

In spite of the numerous advantages of LDs in with their numerous advantages still lack attention due to high cost, health hazard issues, color mixing complexity, and efficient homogenous illumination purpose. Previously LDs, emitting in infrared (IR), have been employed for mobile data communication with data rates up to 1.25 Gbps [15].Non-return-to-zero on-off-keying (NRZ-OOK) modulation scheme, employed by Watson et al., has preliminarily demonstrated a 2.5 Gbps free-space link [16] but with the inherent transmission capacity limitation due to inefficient modulation format. Using QAM OFDM modulation on a single blue LD, Lin's group was able to achieve 9 Gbps data rate [17]. To achieve laser based lighting, Tsao et al., by diffusing four color LDs, demonstrated white light with encouraging results [18]. Haas et al. in his recent work showed white light generation using commercially available RGB LDs and simultaneously transmitting data on individually modulated devices with data rates above 4 Gbps in their visible light communication (VLC) set-up [19]. Unlike the previous investigations, the current work studies the viability of generating white light via laser based RGB color mixing, and in parallel implementing LD-based VLC capabilities. Our concurrent implementation of VLC and white light generation showed red LD with the highest data rate 4.4 Gbps, and maintaining good color temperatures, while the blue and green LDs also showed a data rate of up to 4 Gbps.

2. Experimental description



(a) Set-up diagram (b) Set-up

Fig. 1. Experimental setup for white light based visible light communication.

The experimental setup is shown in Fig. 1. RGBLDs were used to generate white light by passing the laser beam through a commercially available diffuser. The LDs, red (LP642-

SF20), green (LP520-SF15), and blue (LP450-SF15) from Thorlabs, exhibits a nominal spectral linewidth / center wavelengthof1 nm/640 nm, 0.48 nm/515 nm, 0.9 nm /447.2 nm, respectively. Plano-convex lenses (LA1951-A) were used in front of the emitting devices to collimate the laser beams. To obtain white light, the beams were aligned in a single path with the help of a mirror (BB2-E02) and two beam splitters (BP145B1) with a splitting ratio of 45/55. After passing through the diffuser, the diffused and mixed white light is then collected using a focusing lens(LA1131) and focused onto an avalanche photodiode (APD210 by Menlo systems, detector diameter of 0.5mm) with selected band-pass filter in between. Distance from the diffuser to the detector was kept at ~20cm. Three band pass filters (FB (450/520/640)-10) were utilized to allow only the wavelength with modulated data to reach the photodetector.

Intensity modulation can be utilized to encode data on the LDs for incoherent visible light communication. The modulating scheme utilized for this purpose was based on 16-QAM OFDM. The versatile OFDM data bandwidths were generated by a homemade MATLAB program with a FFT size of 512,a cyclic prefix(CP)of 1/32, and 8 long training symbols. The training symbols were produced using a QPSK-OFDM data with a ratio of 12.5%. The data was uploaded into an arbitrary waveform generator (Tektronix, 70001A) with a sampling rate of 24GSa/s. In this work, a fixed AWG sampling rate is set for adapting different OFDM data bandwidths, which helps to develop the maximal data rate of RGB lasers. The subcarrier number (N) is calculated by

$$N = f_B \times \frac{FFT\ size}{sampling\ rate} \tag{1}$$

with f_B and *FFT size* defining the OFDM data bandwidth and the fast Fourier transform, respectively [20]. During experiments, the used of 16-QAM OFDM data with bandwidths of 1, 1.1 and 1.2 GHz are ranged from 0.14 to 1.14 GHz, from 0.14 to 1.24 GHz and from 0.14 to 1.34 GHz, respectively, which reveals related subcarriers of21, 24 and 26. In addition, the ratios of training sequence (TS), CP and FEC overhead are 3.1%, 12.5% and 7%, respectively. After removing the TS, CP and FEC overhead, the efficient data rates can be calculated as 3.096, 3.406 and 3.715 Gbps for the 1, 1.1 and 1.2GHz 16-QAM OFDM data, respectively verifying the maximal transmission capacity of white light. Using an ultra-broadband amplifier (Picosecond Pulse Labs, 5865) of 26.5dB gain, the AWG output electrical signal with the optimized 16-QAM OFDM data was pre-amplified to modulate the pigtailed RGB lasers. The 16-QAM OFDM data was fed into the packaged LDs from the built-in RF input of pigtailed driver (LDM9LP). The modulated light was then transmitted in free-space, and an APD with a −3dBcut-off frequency of 1GHz was used to receive the data. The received optical powers for the RGB LDs were 0.22 mW, 0.090 mW and 0.073 mW, respectively.After optoelectronic conversion inside the APD, the received 16-QAM OFDM data was captured by a digital serial analyzer (Tektronix, DSA71604C) with a sampling rate of 100 GSa/s and analyzed using the homemade MATLAB program. For demodulation, the received OFDM data after re-sampling by a real-time scope is passed through a symbol synchronization which utilizes an auto-correlation algorithm to calculate a correlation coefficient for the received training symbol, which estimates the relative position of QAM OFDM data to find its head. After removing the CP, a frequency domain equalizer (FDE) is employed to recover the received OFDM data. Simultaneously, the FDE program is also combined with the FFT program to transform the QAM OFDM data from time-domain to frequency-domain. After S/P conversion, all subcarriers are re-mapped back to the M-QAM symbols such that its error vector magnitude (EVM), SNR and BER performances can be calculated. The EVM and SNR of the n_{th} OFDM subcarrier can be calculated by using the following equation:

$$EVM(n) = \sqrt{\frac{\left|S_r(n) - S_t(n)\right|^2}{P_0(n)}} \approx \sqrt{\frac{1}{SNR(n)}} \tag{2}$$

where $S_r(n)$ denotes the normalized received n_{th} symbol which is corrupted by the channel noise, $S_t(n)$ the ideal value of the n_{th} symbol and $P_0(n)$ the maximum normalized power of ideal symbol [21]. Therein, the subcarrier EVM is obtained through symbol-to-symbol comparison. In addition, since the EVM is the square root of the reciprocal of SNR, the subcarrier SNR can thus be obtained. Channel performance was estimated using subcarrier SNRs of the received QAM OFDM signal. Since this work is focused on developing the maximal data rate of red, green, blue and mixed-RGB white LDs, the high oversampling rate is employed to overcome the frequency selective fading of transmitted data at a cost of slightly increased inter-carrier interference (ICI).

3. Results and discussion

Figure 2(a)-(c) shows the light-output – current – voltage (L-I-V) curves of the pigtailed RGBLDs having threshold current of 59.7mA, 50.6mA and 34.0mA and slope efficiency of 39.7%,16.7% and 22.2%, respectively. The lasing wavelengths for the RGB LDs are 640 nm, 515nm, and 447.2 nm; while the corresponding full-width at half-maximum (FWHM) are ~1 nm, ~0.48nm, and ~0.9 nm, respectively, as shown in the insets for each figures.

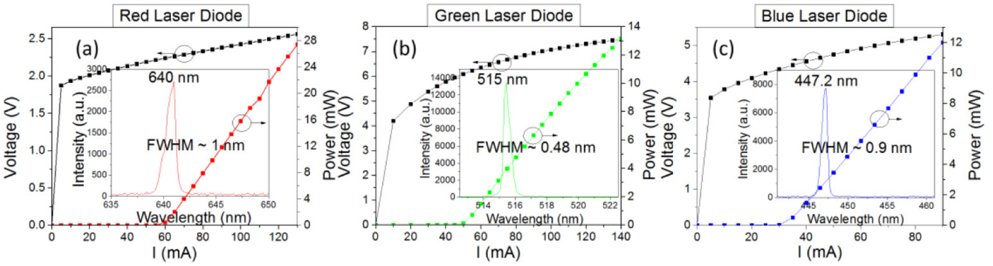


Fig. 2. Light output power – current – voltage (L-I-V) characteristics and above threshold emission spectra of the (a) red, (b) green and (c) blue LDs.

As a figure of merit, the frequency response of the three lasers for the allowable encoding bandwidth and transmission performances is characterized. Figure 3 shows the small-signal frequency response of RGBLDs with different DC bias currents. With the increase in DC bias level, the red LD bandwidth is slightly extended due to up-shift of its relaxation frequency and gain. However for the green LD the up-shift can be attributed to an increase in transmitter power. No significant shift in bandwidth is observed for the blue LD. The most likely cause of the decrease in throughput intensity at high frequency region is the 1 GHz cut-off frequency of the APD. As a consequence, the allowable OFDM bandwidth is also confined due to these constraints. After measuring the frequency response, the −3dB bandwidths of RGB systems (including the AWG, the RGB LDs, the LD driver, the PD, and the DSA)are1.18, 1.15, and 1.02GHz, respectively. When comparing with the of-the-shelf LEDs [7], LDs exhibit couple order of modulation bandwidths so as to produce a high performance and data rate communication.

#240960 Received 18 May 2015; revised 25 Jun 2015; accepted 27 Jun 2015; published 10 Jul 2015

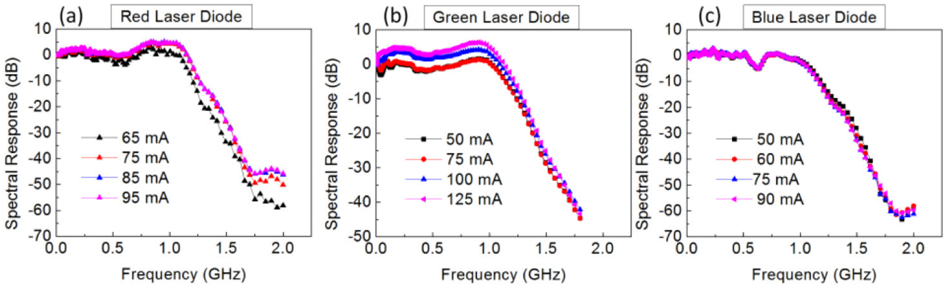


Fig. 3. Bandwidth response of:(a) red, (b) green and (c) blue LDs.

The transmission performance of three LDs under different biases was investigated. The LDs were individually encoded with 1GHz 16-QAM OFDM data. Constellation diagram and BER were analyzed as shown in Fig. 4.

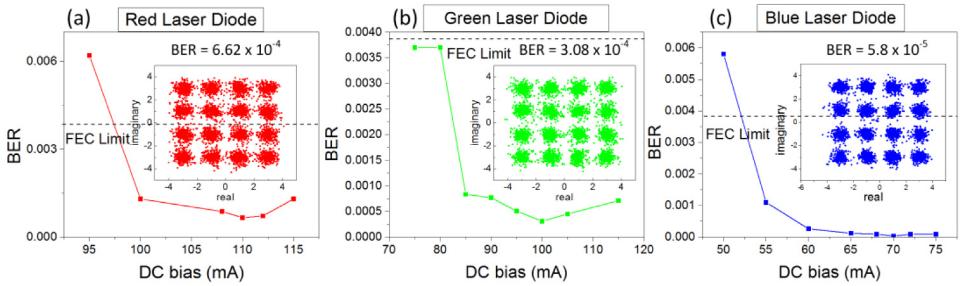


Fig. 4. Bit error rate vs. DC bias current of (a) red, (b) green and (c) blue LDs, with 1GHz 16-QAM OFDM data.

When modulating the LD above threshold, the optimized operating conditions of 110, 100 and 70 mA were observed for RGB LDs with generated optical powers of 19.19 mW, 7.833 mW and 7.68 mW, respectively. At low DC bias current, clipping of the modulated signal degrades the BER of encoded 16-QAM OFDM data. In addition, overly biased operation declines the laser throughput response to degrade the high-frequency subcarrier power of 16-QAM OFDM data, which increases the transmitted BER. The peak-to-peak modulation voltages of 0.4, 0.3 and 0.4 V were amplified to 5.98, 6.34 and 3.18 V for RGB LDs, respectively. After modulating with above amplitudes, the bias currents of RGB LDs are respectively detuned to optimize the carried OFDM data with improved BERs, which is contributed by avoiding the waveform clipping and maximizing the data extinction ratio simultaneously.

For white light experiment, the bias levels for RGB LDs were set at 110, 100 and 70mA respectively. Based on the setup shown in Fig. 1, best operating conditions were obtained for the RGB LDs. Individually LDs were independently modulated using 1, 1.1, 1.2GHz 16-QAM OFDM data. The diffused white light spectral characteristics, corresponding to the intensity ratio between the red, green and blue, were measured with a GL Spectis 5.0 Touch spectrometer. The diffused light spectrum along with the white light color coding and correlated color temperature (CCT) based on CIE 1931 standard for the RGB LDs at operating conditions, are shown in Fig. 5.

The intensities of the two LDs not being encoded were varied to get good white light color temperatures by varying the DC bias conditions. Modulated laser was kept in the optimized operating condition mentioned above. Since the white light characteristics drastically changes with blue light intensity, optical density (OD) filters were used to improve for better results.

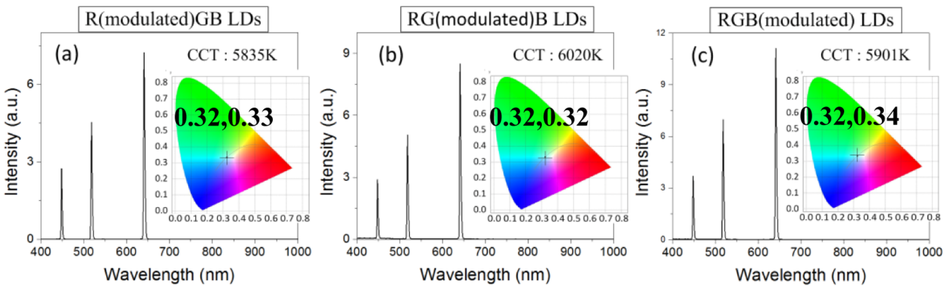


Fig. 5. Diffused light spectra with white light characteristics shown in the inset with 16-QAM OFDM encoding done on: (a) red (b) green and (c) blue LDs.

The goal of this study is to achieve highest possible data rates, with BER meeting the FEC standard (BER ≤ 3.8×10^{-3}) and white light with CCT value of 5500 K. The transmission distance from the diffuser to the photodetector was approximately ~20 cm. The LDs were modulated at optimized conditions and no laser spot was observed after passing through the diffuser. The transmission results for different data rates are summarized in Table 1. When modulating the red and green lasers, an OD 0.4 filter was placed in front of the blue LD to improve white light characteristics. When modulating the blue LD, the strength of the OD filter was reduced to improve BER at the expense of cooler white light.

Table 1. Results of BER/SNR/EVM for different data rates.

Data rate (Gbps)	BER/SNR/EVM		
	Red LD	Green LD	Blue LD with OD 0.2 filter
4	5.0×10^{-4}/17.1/13.9	1.4×10^{-3}/16.3/15.4	2.8×10^{-3}/15.5/16.7
4.4	3.3×10^{-3}/15.3/17.9	4.6×10^{-3}/14.9/17.8	1.0×10^{-2}/13.9/20.3
4.8	6.3×10^{-3}/14.6/18.7	-	-

As can be noticed from Table 1,the highest data rate of 4.4 Gbps with a BER of 3.3×10^{-3} was achieved when encoding the red LD. Blue and green LDs only achieved data rate of 4 Gbps with BERs of 2.8×10^{-3} and 1.4×10^{-3}, respectively. The better performance of the red LD is mainly attributed to the higher light intensity at the receiving end, resulting in larger extinction ratio of the received signal.

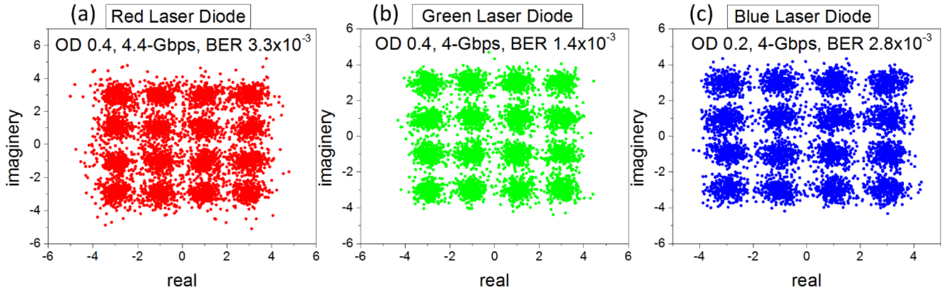


Fig. 6. Constellation diagram of 16-QAM OFDM for the highest data rates obtained for (a) red, (b) green and (c) blue LDs meeting the FEC criteria.

The constellation diagrams of three LDs carrying16-QAM OFDM data are shown in Fig. 6. When encoding the blue LED, to pass the FEC criteria, OD filter strength was decreased from 0.4 to 0.2 to increase the modulated light intensity. Briefly, we demonstrated that all three LDs can be modulated with data rates up to 4 Gbps.

Table 2. Bit error rate(BER) and correlated color temperature (CCT) measurements when encoding blue LD with 4 Gbps16-QAM OFDM data at different strengths of OD filters.

OD Filter Strength	BER	CCT (K)
0	1.5×10^{-3}	12000
0.1	1.5×10^{-3}	9020
0.2	2.8×10^{-3}	7000
0.4	5.1×10^{-3}	5901

To gain insight into how the extinction of the received signal depends on the received light intensity, the BER of the modulated blue LD was measured at varying OD filter strengths. The LD was operated at the optimized DC bias of 70mA. As shown in Table 2, an expected improvement in BER was noticed with an increase in the blue LD intensity. This is attributed to larger received signal amplitude. On the contrary, stronger blue LD intensity significantly increases the CCT value resulting in poorer white light characteristics. To achieve low BER, the use of OD filters can be avoided by increasing the intensity of red and green LDs. In our experiments, such adjustment was limited by the use of beam splitters and the upper safe-operating limits of the red and green LDs. It is worth mentioning that without the diffuser, blue LD gave the best BER results as shown in Fig. 4. However for white light based VLC, red LD provides the highest data rate of 4.4Gbpswith stronger received signal intensity.

4. Conclusion

Concurrent implementation of RGB LDs based white light illumination and16-QAM OFDM VLC was demonstrated in this work. Based on the throughput optimization using 1GHz 16-QAM OFDM data, the red, green and blue LDs operating conditions were found to be at 110, 100 and 70mA, respectively. With red LD, we achieved the highest data rate of 4.4Gbpswith a BER of 3.3×10^{-3}, which is mainly attributed to larger extinction ratio of the received signal. Also, white light with CCT value of 5835K (the color temperature within the range of daylight illumination)in conjunction with the above high data rate was easily obtained when encoding the red LD. When encoding blue LD to meet FEC criteria for 4Gbps, light intensity has to be increased, but as a result, a cooler diffused white light with CCT above 7000Kup to 12000 K was obtained, demonstrating the inevitable trade-off between color temperature control and transmission data rate for the blue LD. This study highlighted a preferable encoding scheme by using red LD to carry direct 16-QAM OFDM data for visible light communication and white light illumination.

Acknowledgments

Bilal Janjua gratefully acknowledges the financial support from King Abdulaziz City for Science and Technology (KACST) and king Abdullah University of Science and Technology (KAUST), under the Technology Innovation Center (TIC) program and base line funding.

#240960 Received 18 May 2015; revised 25 Jun 2015; accepted 27 Jun 2015; published 10 Jul 2015