Compact High-Power Visible Laser Diode Wavelength Division Multiplexing for White-Light Communication

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For compact ultrahigh-power lighting and high-speed optical wireless communication (OWC) purposes, the red/green/violet laser diodes (R/G/V-LDs) modulated with specific Subminiature A (SMA) connectors are used for cold white-light mixing and direct digital encoding. Even with hybridizing a high-power yellow light-emitting diode (LED) for high color-rendering index lighting, such a R/G/V-Y design can miniaturize its volume to \( W \times L \times H = 6 \times 5.4 \times 2 \text{ cm}^3 \) (only 1/310 of the conventional bulky setup). The R/G/V-LDs are individually encoded by 16 quadrature amplitude modulation orthogonal frequency-division multiplexing (16-QAM OFDM) data to demonstrate the visible wavelength division multiplexing (VWDM). Such R/G/V-LD VWDM transmitters provide 8.8/5.2/7.2 Gbps modulation to achieve the total data rate as high as 21.2 Gbps after employing the power preleveling technique. Such high-power R/G/V-LDs under optimized bias currents deliver an output power of 102/97/129 mW, which can offer a high illuminance of 12 800 lux within a divergent angle of 54° at a distance of 0.5 m. To date, such ultrahigh-power compact R/G/V-LDs with lighting VWDM capability beyond 20 Gbps also enable the possibility of network coverage for 5G and Industry 4.0 applications.

1. Introduction

Nowadays, visible lighting communication (VLC) has emerged as an exceptional candidate for expanding the network coverage, which can fulfill the demand of data access via high-speed free-space-optical (FSO) networks.[1–7] The VLC also serves as a member of the lighting fidelity (Li-Fi) family, which supplements the local access network with better security and higher capacity than the wireless fidelity (Wi-Fi). At the early stage, Khalid et al. used a white-lighting light-emitting diode (LED) to enable optical wireless communication (OWC) with discrete multitone (DMT) data at 1 Gbps that exceeds the data rate over 100 times than traditional Wi-Fi.[8] Later on, a blue laser diode (LD) is used to construct the OWC up to 4 Gbps.[9] In the 2011 TED Global talk, Haas declared the limitation on certified Wi-Fi bandwidth, whereas Li-Fi allows broader bandwidths as more unlicensed bands are applicable in the optical domain.[10] In particular, the white-lighting OWC can provide diversified lighting scenarios with qualified data transmission, which enables indoor/cabin VLC, underwater OWC, and point-to-point FSO data links. For example, Wang et al. used the RGB-LEDs mixed white light to carry 512 quadrature amplitude modulation orthogonal frequency-division multiplexing (512-QAM OFDM) data at 4.22 Gbps.[11] Dursun et al. used a perovskite phosphor with a shortened luminescent lifetime to color-convert a blue LD for white-lighting data transmission at 2 Gbps.[12] Shen et al. demonstrated a blue-LD underwater wireless optical communication (UWOC) at 1.5 Gbps over 20 m.[13] More recently, a 5.4 m long blue-LD UWOC with 16-QAM OFDM at 4.8 Gbps was achieved.[14] Wu et al. prelevelled the data amplitude to improve QAM OFDM up to 7.2 Gbps over 6.8 m in seawater.[15] To realize vehicle-to-vehicle and vehicle-to-roadside communications, the Li-Fi not only immunes from electromagnetic interference but also sustains in a harsh environment. These make the Li-Fi suitable for intelligent transportation systems (ITSs) in heavy traffic congestion by integrating with car headlights, street lamps, and traffic signs. In 2001, Akanegawa et al. proposed the first OWC for ITS[16] by implementing the LED traffic light-based road-to-vehicle link. Such LED Li-Fi systems have successfully delivered the pulse position modulation (PPM) data format at 1 Mbps,[17] triggered the vehicle-to-vehicle link at 10 kbps over 30 m in daytime,[18] and urged the LED car headlight VLC beacon for 3.1 Mbps transmission.[19]

Although white-light LED was the most popular VLC source with 16-QAM OFDM improving from 1.6[20] to 3 Gbps,[21] and the micro-LED with smaller capacitance can support the higher data rate up to 5 Gbps.[22] Nevertheless, the LED source still suffers from low modulation bandwidth and intense efficiency droop. Alternatively, Chi et al. used blue LD with broad modulation bandwidth and large power efficiency to deliver QAM OFDM

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at 9 Gbps. Singh et al. constructed a red-LD OWC at 10 Gbps. In 2015, the red-LD FSO link with 25 Gbps data over 10 m was reported. For white lighting, either the phosphor adhered blue/violet LD or the tricolor-LD solution was proposed previously. The blue or violet LD color-converted white lighting via the inorganic phosphor has elevated the OWC data rate to several Gbps in a few years. However, the transmission speed is seriously degraded as most LD power is wasted during color conversion. The RGB-LD or the RGV-D mixed white light has emerged to improve the data rate without sacrificing the lighting illuminance. Wang et al. used the RGB-LDs to carry on-off keying (OOK) data at 9.7 Gbps over 2.3 m in the underwater environment. Later on, the allowable data rate was further promoted to 20 Gbps and up to 100 Gbps with a 36 channel WDM system. Wei et al. used the bit-loading, power-loading, and polarization multiplexing technologies to improve the data rate beyond 40 Gbps. Meanwhile, the RGB-LDs-based underwater OWC at 9.51 Gbps over 10 m was also reported, however, its color-rendering index (CRI) is unqualified for lighting due to the narrow spectral linewidth. After adding the yellow LED (Y-LED) with a wider emission spectrum, Janjua et al. reported the RGV-LDs+Y-LED mixed white light with a high CRI beyond 85. In previous works, most RGB-LDs+Y-LED white-light OWC module was still too bulky in size.

A collimated beam combiner module is designed with its size shrinking from $W \times L \times H = 45 \times 30 \times 15 \text{ cm}^3$ to $W \times L \times H = 6 \times 5.4 \times 2 \text{ cm}^3$ to develop a miniaturized RGVY white-lighting module for the OWC link in this work. Such a volume shrinkage by a factor of 1/310 makes the compact and simplified white-light OWC system RGV-LDs+Y-LED source. The high-power R/G/V-LDs are used to increase the illuminance and demonstrate the eye-safe data transmission, which can also serve as the car headlight for vehicle-to-vehicle communication. To improve the improved CRI, the high-power RGV-LDs+Y-LED module mixed white-lighting OWC is integrated by using a 638 nm RLD with a rated power of 700 mW, a 520 nm GLD with a rated power of 900 mW, a 405 nm VLD with a rated power of 250 mW, and a Y-LED with a rated power of 83 mW. This RGV+Y white-light module also serves as the optical data transmitter for carrying the 16-QAM OFDM data. The bias current of each LD is optimized to enlarge the lighting illuminance, and the sampling rate of each encoding data stream is adjusted to maximize the transmission data capacity with the high-power R/G/V/Y module. By employing the power preleveling to compensate for the declined modulation throughput at the high-frequency region, the extreme data rate of such a visible wavelength division multiplexing (VWDM) link is performed. Under distant illumination with a divergent angle equivalent to that of the commercial car headlight module, such compact R/G/V/Y mixed VWDM unit remains its intense lighting with cold white-light correlated color temperature (CCT) and high CRI in detail to perform the car-light application in the future. To date, the ultra high-power R/G/V-LDs VWDM lighting module can provide a transmission data rate beyond 20 Gbps, which also enables the possibility of the 5G/6G and the Industry 4.0 network coverage in the next generation.

2. Experimental Section

Figure 1 shows the miniaturized high-power R/G/V/Y white-lighting module as compared to the bulky optomechanical module architected with typical design. The bulky module exhibited a volume of $W \times L \times H = 45 \times 30 \times 15 \text{ cm}^3$, whereas the size of the...
The miniaturized R/G/V/Y module was designed with \( W \times L \times H = 6 \times 5.4 \times 2 \text{ cm}^3 \), which greatly reduced the volume by more than 310 times. To construct the high-power RGVY white-light, the 638 nm RLD (Oclaro, HL63193MG), the 520 nm GLD (New Nichia, NUGM02T), the 405 nm VLD (New Nichia, NDV4512), and the 595 nm YLED were used as the lighting components. In a conventional system, numerous opto-mechanical mounts must be used to individually allocate the LDs, collimating lenses, beam combiner, reflector mirrors, translation stages, and diffusers. If each element required at least \( 9 \times 9 \text{ cm}^2 \) in the space area for flexible alignment, each colored LD/LED line needed at least four holders/mount/stage sets for completing the RGB(V)-LD + Y-LED module, the smallest module would be larger than 1350 cm\(^2\). In contrast, this work designed a 4-in-1 module for each line with a prealigned mini-mount to precisely allocate all elements in four lines with shrinking space area. There was still a tiny tolerance for fine alignment among LD/lens/combiner/mirror component holders, and the whole space area of such a compact submount module can be reduced to \( 6 \times 5.4 \text{ cm}^2 \).

The respective dichroic beam combiners were used to combine the colored light beams, and their spectra are shown in Figure 2. In front of the GLD, the reflectance spectra of the selected mirror prism revealed a reflectance (R) of more than 0.98 at 520 nm, as shown in Figure 2a. A dichroic mirror (Lasertack, DM-A) with a transmittance (T) of 0.99 @ 520 nm and a cutoff transmittance of 0.04 @ 595 nm was placed in front of the 595 nm YLED, as shown in Figure 2b. The dichroic mirror can reflect the yellow light to combine with the transmitted green light. Next, another dichroic mirror (Semrock, FF614-SDi01) with transmittances of 0.95 @ 520 nm, 0.97 @ 595 nm, and 0.01 @ 638 nm was placed in front of the 638 nm RLD, as shown in Figure 2c. The delivered green and yellow light beams mixed with the red light beam reflected by the dichroic mirror. The last dichroic mirror (Lasertack, DM-B) was in front of the 405 nm VLD with \( T = 0.98 \) at 520 nm, \( T = 0.99 \) at 595 nm, \( T = 0.98 \) at 638 nm, and \( T = 0.02 \) at 405 nm, as shown in Figure 2d. The delivered green, yellow, and red lights mixed with the reflected violet light to generate white light after passing through the last dichroic reflector.

The packaged high-power R/G/V/Y white-lighting module and combined light traces are shown in Figure 3a,b. These high-power R/G/V TO-can LDs and Y-LED were plugged into the specific designed Subminiature A (SMA) connectors to connect with the bias-tee for bias-current and data-stream combination. The sets of the TO-can LD + SMA connector were screwed on to the mini-imized beam combiner module. For beam collimation, four AR (antireflective)-coated glass lens collimators with the same focal length of 1 cm were installed in front of the R/G/V-LDs and YLED to make the parallel beams performing chromatism free beam spot. In this module, the green light was first reflected by a mirror prism, and the related dichroic mirrors individually reflected the other three color lights. After aligning the four-color light beams to the same collimating axis, a frosted glass diffuser, which suppressed the chromatic aberration and expanded the divergent angle, was used to diverge the mixed white light source. The whole miniaturized R/G/V/Y module was temperature controlled at 25°C by using a homemade self-feedback temperature controller with a thermistor and TE cooler.

**Figure 2.** Transmission spectra of the reflector mirror and dichroic mirrors. a) The spectra of the mirror prism placed in front of the GLD, b) the dichroic mirror placed in front of the YLED, c) the dichroic mirror placed in front of the RLD, and d) the dichroic mirror placed in front of the VLD.
for the decoding algorithm in this work. During experiments, the high-power Y-LED was not used as a transmitter because of its extremely low modulation bandwidth. To measure the R/G/V/Y mixed white-lighting performance, the CCT, CRI, and CIE coordinates were analyzed by a colorimeter (OKTEK, GL-2), and its divergent illuminance was measured with a lux meter (TECPEL, 530).

3. Results and Discussions

3.1. Output Characteristics of the R/G/V-LDs and Y-LED

Figure 4a shows the power-to-current (P–I) curves of the high power R, G, and V LDs threshold currents of 210, 184, and 35 mA and emission efficiencies (dP/dI slopes) of 0.55, 0.48, and 0.85 W/A, respectively. Although the rated powers of these R/G/V-LDs are, respectively, 700, 900, and 250 mW, their optimized operations under direct modulation only provide an average output of 102 mW (I_{RLD} = 345 mA), 97 mW (I_{GLD} = 345 mA), and 129 mW (I_{VLD} = 180 mA), respectively. This reason is somewhat limited by the finite data amplitude provided with the AWG. Figure 4b,c show the voltage-to-current (V–I) curves and the differential resistances (dV/dI) of tricolor LDs in which all dV/dI curves dramatically degrade before lasing to reach 0.92 Ω for RLD, 1.58 Ω for GLD, and 8.15 Ω for VLD at optimized biases. The dV/dI of much smaller than 50 Ω causes the impedance mismatched reflection of modulation. The corresponding microwave reflectance (Γ) of −0.96, −0.94, and −0.72 and the voltage standing wave ratio (VSWR) of 49, 32.3, and 6.14, and the corresponding return loss (η_{RL}) of 0.35, 0.54, and 2.85 dB can be estimated, respectively.

Figure 5 shows the analog modulation frequency response of the high-power R/G/V-LDs at different bias currents to optimize the bias current for broadening the encodable bandwidth. The upshift of relaxation oscillation peak extends the throughput response toward the high-frequency region. As a result, the −3 and −6 dB bandwidths of the RLD broaden to 2.05 and 2.25 GHz when biasing at 350 mA, as shown in Figure 5a. With increasing the bias from 300 to 500 mA, the relaxation oscillation peak significantly upshifts from 1.0 to 1.8 GHz. The frequency response of the GLD shown in Figure 5b only exhibits the −3 and −6 dB bandwidths of 1.27 and 1.31 GHz with its relaxation oscillation peak slightly shifted from 0.99 GHz at 300 mA to 1.2 GHz @500 mA. Figure 5c shows the modulation frequency response of VLD with its −3 and −6 dB bandwidths of 0.65 and 1.35 GHz under a bias at 180 mA. Nevertheless, the VLD also reveals the most flattened modulation throughput among all LDs used in this work. After the −3 dB decaying point, the declined slope of the modulation throughput for R/G/V-LDs is determined as −11.2/−10.7/−4.2 dB GHz⁻¹.

Due to the broadband spontaneous emission and low modulation bandwidth of the LED, the high-power Y-LED is only used for upgrading the CRI performance of the R/G/V/Y white-lighting module. Figure 6a shows the P–I–V curve response of the Y-LED with its maximal output power of 83.1 mW when
setting the forward bias voltage at 3.2 V. The luminescent spectrum of the Y-LED is shown in Figure 6b, which reveals the peak wavelength at 595 nm and the FWHM of 26 nm. The inset of Figure 6b shows the photographs of the Y-LED after installing it into the beam collimator module.

3.2. Data Transmission Performance of the R/G/V-LD + Y-LED Mixed White-Lighting Module

The bias currents of the R/G/V-LDs and the sampling rate of the QAM-OFDM data need to be adjusted individually, which further maximizes the data transmission capacity. Figure 7 shows the optimization on the bias-dependent 16-QAM OFDM performances of the R/G/V-LDs. With increasing bias, the upshifted relaxation oscillation and the suppressed relative intensity noise (RIN) effectively improve the SNR and BER before the waveform clipping phenomenon occurs. Usually, the bias results in either the throughput power saturation (waveform clipping) or the on/off data extinction ratio reduction (low efficiency), which inevitably degrades the receiving BER performance with blurred constellation plot after decoding, as shown in the curves beyond the optimization point. By raising the RLD current from 335 to 345 mA, the EVM of the received 2 GHz 16-QAM OFDM data is reduced from 17.4% to 16.7%. These results also improve its BER from $3.9 \times 10^{-3}$ to $2.8 \times 10^{-3}$, as shown in Figure 7a. Further increasing the bias to 355 mA conversely enlarges its EVM to 17.8% with a degrading BER of $4.6 \times 10^{-3}$. Similarly, Figure 7b shows that the GLD delivered 1.2 GHz 16-QAM OFDM data exhibits the smallest EVM of 16.4% with the lowest BER of $2.4 \times 10^{-3}$ when biased at 345 mA. The bias-optimized VLD at 180 mA can carry the 1.6 GHz 16-QAM OFDM with the EVM of 15.3% and the BER of $1.3 \times 10^{-3}$.

The sampling rate optimization of the AWG synthesized data stream is performed and shown in Figure 8. With the subcarrier SNR spectrum in Figure 8a, the sampling-rate dependent BER of the RLD carried 2 GHz 16-QAM OFDM indicates that the SNR...
can increase from 14.94 dB to 15.54 dB with BER improving from $4.7 \times 10^{-3}$ to $2.8 \times 10^{-3}$. Oversampling rate up to 16 GS s$^{-1}$ (with a corresponding subcarrier number of 64) degrades the SNR to 14.2 dB with a corresponding BER of $8.1 \times 10^{-3}$. Likewise, Figure 8b,e show that with increasing the sampling rate from 4 to 8 GS s$^{-1}$ (with subcarrier number decreasing from 154 to 77), the subcarrier SNR of the 1.2 GHz 16-QAM OFDM data enhances from 14.3 to 15.7 dB and the BER improves from $7.8 \times 10^{-3}$ to $2.4 \times 10^{-3}$, whereas oversampling to 12 GS s$^{-1}$ degrades the SNR to 14.7 dB and the BER to $5.6 \times 10^{-3}$.

The subcarrier SNR and the corresponding BER responses shown in Figure 8c,f declare that the VLD delivered 1.6 GHz 16-QAM OFDM data can be optimized at 8 GS s$^{-1}$ with the largest SNR of 16.3 dB and the lowest BER of $1.3 \times 10^{-3}$. The last optimization to perform the power preleveling after bias current and sampling rate adjustments can enhance the beyond-bandwidth throughput response to further reduce the received BER. In detail, Figure 9a shows the BER versus preleveling slope for the RLD delivered 2.2 GHz 16-QAM OFDM data. By increasing the preleveling slope from 0.1 to 0.3 dB GHz$^{-1}$, the received BER can be improved from $4.6 \times 10^{-3}$ to $3.7 \times 10^{-3}$; however, the preleveling slope up to 0.5 dB GHz$^{-1}$ would sacrifice the subcarrier power at the low-frequency region to cause the BER degraded to $6.7 \times 10^{-3}$.

Figure 9b shows the received radio frequency (RF) spectra before and after optimized preleveling with an enhanced carrier-to-noise ratio (CNR) of 12 dB after preleveling. Figure 9c shows the constellation plots with EVM improving from 18.7% to 17.3%. Figure 9d shows that the high-frequency subcarrier SNR can be significantly improved after preleveling.

The required SNR under the FEC criterion for the QAM–DMT data can be acquired by the following formula:

$$BER \approx \frac{2 \left(1 - \frac{1}{\sqrt{M}}\right)}{\log_2 M} \times \left\{erfc\left[\sqrt{\frac{3\text{SNR}}{2(M-1)}}\right] + \text{erfc}\left[3\sqrt{\frac{3\text{SNR}}{2(M-1)}}\right]\right\}$$

where $M$ denotes the QAM level. Under the BER criterion under the FEC limit of $3.8 \times 10^{-3}$, the required SNR for the 16-QAM OFDM data can be estimated as 15.1 dB by Equation (1). Note that the distinct SNR dip at 0.8 GHz before preleveling is attributed to the noise from APD. In brief, the allowable bandwidth of the 16-QAM OFDM data stream delivered by the RLD is 2.2 GHz with its EVM of 17.3 %, SNR of 15.2 dB, and BER of $3.7 \times 10^{-3}$ after preleveling.

For the GLD, Figure 10a provides the optimization of BER via preleveling slope adjustment to show that the BER can be decreased to $3.7 \times 10^{-3}$ by reducing the preleveling slope to 0.1 dB GHz$^{-1}$. The RF spectrum of the GLD carried 1.3 GHz 16-QAM OFDM data shown in Figure 10b exhibits a CNR of 11 dB after preleveling. Figure 10c shows that the constellation plot improves its EVM from 17.8% to 17.4% with preleveling, and the subcarrier SNR spectrum in Figure 10d shows the high-frequency SNR improvement after the preleveling technique. The GLD maximizes its 16-QAM OFDM bandwidth to 1.3 GHz with EVM of 17.4 %, SNR of 15.2 dB, and BER of $3.7 \times 10^{-3}$. 

Figure 7. Transmission performance of QAM OFDM data delivered by R/R/G/V LDs. The receiving BERs of a) the 2 GHz 16-QAM OFDM data delivered by RLD, b) the 1.2 GHz 16-QAM OFDM data delivered by GLD, and c) the 1.6 GHz 16-QAM OFDM data delivered by VLD at different biases.
Regarding the VLD, the optimized preleveling slope for the transmitted 1.8 GHz 16-QAM OFDM data is shown in Figure 11a, which improves the received BER from $4.7 \times 10^{-3}$ to $3.1 \times 10^{-3}$ by adjusting the preleveling slope from 0.2 to 0.4 dB GHz$^{-1}$. The BER degraded to $4.9 \times 10^{-3}$ when oversetting the preleveling slope to 0.6 dB GHz$^{-1}$. The RF spectrum of the VLD carried data after preleveling enhances its CNR to 17 dB after preleveling, as shown in Figure 11b. The constellation plot becomes less blurred after preleveling with a smaller EVM of 16.9%, as shown in Figure 11c. Figure 11d shows that the subcarrier 16-QAM OFDM SNR at 1.8 GHz with improved EVM of 16.9%, SNR of 15.4 dB, and BER of $3.1 \times 10^{-3}$.

For the RLD directly encoded by 16-QAM OFDM at 2.2 GHz, the received BER significantly reduces from $6.2 \times 10^{-3}$ to $3.7 \times 10^{-3}$ with its bandwidth penalty decreasing by 0.1 GHz after power preleveling, as shown in Figure 12a. Consequently, the maximal transmission bandwidth of 2.2 GHz enables the high-power RLD to carry the 16-QAM OFDM data up to 8.8 Gbps. Similar improvement on received BER of the GLD delivered data before and after preleveling is shown in Figure 12b, revealing that the encoding bandwidth can be expanded to 1.3 GHz for 5.2 Gbps 16-QAM OFDM with the qualified BER at $3.7 \times 10^{-3}$ after preleveling. Also, Figure 12c shows that the VLD can carry the 16-QAM OFDM at 7.2 Gbps after preleveling with a bandwidth penalty reducing by 0.1 GHz. To sum up, after optimizing the bias-current, sampling-rate, and preleveling slope, the maximal data rate transmitted by the R/G/V-LDs can improve from 2/1.2/1.6 GHz to 2.2/1.3/1.8 GHz, and the total data rate of the high-power R/G/V/Y white-lighting module is increased from 19.2 to 21.2 Gbps.

### 3.3. The R/C/V-LD + Y-LED White-Lighting Performance

Table 1 compares the power and transmission performance of the white-light source based on R/G/B (V) LDs. In 2015,
Figure 9. Transmission performance of the RLD delivered 2.2 GHz 16-QAM OFDM data with/without preleveling. RLD delivered 2.2 GHz 16-QAM OFDM data with its a) BER versus preleveling slope, b) received RF spectra, c) decoded constellation plots, and d) subcarrier SNRs before and after preleveling.

Figure 10. Transmission performance of the GLD delivered 1.3 GHz 16-QAM OFDM data with/without preleveling. GLD delivered 1.3 GHz 16-QAM OFDM data with its a) BER versus pre-leveling slope, b) received RF spectra, c) decoded constellation plots, and d) subcarrier SNRs before and after pre-leveling.
Janjua et al. proposed an RGB-LD mixed white light for transmitting QAM OFDM data at 4.4 Gbps in a free-space link over 0.2 m.\textsuperscript{[40]} In the meantime, Hussein et al. used a similar RGB-LD set to carry OOK data at 5 Gbps.\textsuperscript{[41]} Later on, Wang et al. promoted the data rate of the same system to 9.7 Gbps in the underwater environment.\textsuperscript{[33]} The RGB-LD-based VLC system can deliver the 18.8 Gbps data over 2.5 m by using the bit-loaded 8-256 QAM OFDM format, as demonstrated by Wei et al.\textsuperscript{[42]} In 2018, Wei et al. reported the first 20 Gbps VLC system based on the RGB-LD mixed white light with bit-loading data format.\textsuperscript{[36]} In addition, the polarization multiplexing technology is utilized to improve the data rate beyond 40 Gbps.\textsuperscript{[36]}

Unlike the large and complex set in previous studies, the study in this work employs a compact beam combiner module to miniaturize the system and utilizes high-power LDs to enlarge the illuminance. Even with these long-cavity and high-power LDs, such a R/G/V/Y white-lighting module can still achieve a data rate of 21.2 Gbps and an illuminance as high as 12 800 lux over 0.5 m. To declare the white-lighting performance, Figure 13a shows the photograph of the proposed R/G/V/Y white-lighting spot operating at the optimized bias of 345/345/180 mA for R/G/V-LDs and 3.2 V for Y-LED. For minimizing the color aberration of the mixed white light, a frosted glass diffuser with a roughened surface is used to uniformly diffuse the glaring light from the collimated R/G/V LD beam, as shown in Figure 13b. Moreover, the spotlight of the miniaturized high-power R/G/V/Y mixed white light on a white A4 paper at a distance of 0.5 m away is shown in Figure 13c, which shows the uniform and clean white-lighting spot without any dazzling speckle.

To adjust the GLD power for white-lighting optimization, Figure 14 shows the GLD bias-current-dependent CCT and CRI, which declare the tunability for lighting color of the collimated R/G/V/Y spot in the cold white light regime. The Y-LED is a commercially available device purchased from the Thorlabs website with the product number (M590D2), and there are no details shown on the website regarding device material and configuration.\textsuperscript{[43]} Without adding the Y-LED, the RGV-LD module reveals an extremely low CRI (<30) that is not qualified for lighting. Adding the high-power Y-LED improves the CRI beyond 60.7 that can be certified for using the RGV-LD + T-LED module as a car head lighter. Figure 14a shows the CCT ranging from 4600 to 5500 K and CRI ranging from 40 to 60 for the R/G/V/Y mixed white-light source by tuning GLD bias currents, and the plots of their corresponding CIE chromaticity coordinate at different GLD currents are shown in Figure 14b. The CIE coordinate at (0.3480, 0.3984) is observed with corresponding CCT and CRI of 4646 K and 41.4 at 320 mA. When adjusting the current to 345 mA, a higher CRI of 60.7, which satisfies the general white-lighting demand, is obtained with a CCT of 5176 K at a CIE coordinate of (0.3461, 0.4424). Raising the GLD bias to 360 mA degrades the white-light CRI to 58.8 with a slightly increased CCT of 5408 at a CIE...
coordinate of (0.3374, 0.4488). These analyses confirm the optimized bias current of the GLD is 345 mA for synthesizing the cold white light with qualified CRI from the miniaturized R/G/V/Y module.

Figure 15a shows the performance of distance-dependent illuminance for the high-power R/G/V/Y mixed white-light source as compared to that of the commercial car headlight. By using the frosted glass to uniformly diffuse and mix the collimated LD beams, the illuminance of 39 300 lux is observed at a distance of 15 cm, which is much higher than the illuminance of 20 400 lux for the low beam of the commercial car headlight. When extending the distance to 30 cm, the illuminance of the high-power R/G/V/Y module is decreased to 24 700 lux but still exceeds twice the illuminance provided by the low beam of the commercial car headlight.

Further expanding the lighting distance to 50 cm causes the high-power R/G/V/Y module to decay its illuminance to 12 800 lux, whereas the commercial car headlight only provides a low-beam illuminance of 6400 lux. Figure 15b compares the divergent angle between the R/G/V/Y module and commercial car headlight. The high-power R/G/V/Y module displays a divergent angle of 54° at 30 cm and 63° at 50 cm. In comparison, the divergent angle of the low and high beams provided by commercial car headlight is 80° and 30°, respectively. Although the miniaturized R/G/V/Y mixed white light exhibits higher directivity than the low beam of a commercial car headlight, its radiant angle can be further expanded via the appropriate design of the car lampshade. Due to the large divergent angle designed for the RGV-LD + LD lighting module by adding a frosted glass diffuser, the lighting power density per area is scaled down to well below the damage threshold of human eye. The spectral window that invades the human eye safety is nearly a Gaussian function with a peak wavelength at 437 nm and a –3 dB linewidth of 65 nm. The correlation between the hazard efficiency in the UV-blue light region and the responsivity of the human eye’s spectral response confirms that the hazard factor of violet light to human eye will be 1/5 smaller than that of the blue light. Using the RGV-LD + Y-LED module to replace the RGB-LD + Y-LED set, all of the component wavelengths are almost located outside the eye hazard spectral window to perform the eye-safe lighting and communication. As a summary, Table 2 lists the related lighting parameters for comparisons between the miniaturized high-power R/G/V/Y module and the commercial car headlight. Under the optimized bias current, the high-power R/G/V/Y module can provide a CCT of 5176 K that refers to cold white light. This CCT has already met the specification of commercial car headlight ranged between 3000 and 7000 K. Moreover, the high-power R/G/V/Y mixed white light source exhibits a CRI of 60.7 passed the commercial requirements. Its divergent angle of 54° is broader than the commercial car headlight, which can be further expanded through lampshade design in the future.

Table 1. R/G/V(B)-LD White Lighting Transmission Performance.

| Ref. | LD type   | Power | Distance     | Data format     | Data rate |
|------|-----------|-------|--------------|-----------------|-----------|
| [33] | RGB-LD    | –     | 2.3 m (Underwater) | OOK             | 9.7 Gbps  |
| [34] | RGB-LD    | –     | 1 m          | Bit-loading 8-256 QAM | 20 Gbps  |
| [36] | RGB-LD    | –     | 2 m          | Bit-loading 8-256 QAM | 40.665 Gbps |
| [40] | RGB-LD    | 35 mW | 0.2 m        | 16 QAM         | 4.4 Gbps  |
| [41] | RGB-LD    | –     | –            | OOK            | 5 Gbps    |
| [42] | RGB-LD    | 10.8 mW | 2.5 m | Bit-loading 8-256 QAM | 18.8 Gbps |
|      | RGV-LD + Y-LED | 328 mW | 0.5 m | 16 QAM         | 21.2 Gbps |

Figure 12. BERs of the QAM OFDM data delivered by R/G/V LDs under different data bandwidths with/without preleveling. BER versus bandwidth for the 16-QAM OFDM data carried by a) RLD, b) GLD, and c) VLD before and after preleveling.
Figure 13. White-lighting emission of the miniaturized R/G/V/Y mixed white-lighting module. a) The photographs of the miniaturized R/G/V/Y mixed white-lighting module, b) the frosted glass scattering diffuser, and c) the mixed white-light spot illuminating on white paper.

Figure 14. White-lighting characteristics of the miniaturized R/G/V/Y mixed white-lighting module at different bias currents of GLD. a) The CCTs and CRIs and b) the chromaticity diagrams of the R/G/V/Y module mixed white-light source at different bias currents of GLD.
Conclusion

This work demonstrates a miniaturized high-power RGV-LDs+Y-LED mixed white-lighting module for OWC. The volume of the miniaturized R/G/V/Y module is only $W \times L \times H = 6 \times 5.4 \times 2 \text{ cm}^3$, which is significantly reduced by more than 310 times when compared with that of the bulky RGB-LD white-lighting module architected with typical optomechanical desktop design (with $W \times L \times H = 45 \times 30 \times 15 \text{ cm}^3$). Due to the narrow spectral linewidth of the LDs, a high-power 595 nm Y-LED with broadband spectrum is used to enhance the CRI when performing white-lighting applications. The 16-QAM OFDM data individually encodes the high-power R/G/V-LDs to perform the VWDM scheme, which further improves the data transmission performance of this miniaturized R/G/V/Y module. After adjusting the bias current, the AWG sampling rate, and the preleveling slope, the R/G/V-LDs can achieve the maximal transmission data rate of 8.8 Gbps for RLD, 5.2 Gbps for GLD, and 7.2 Gbps for VLD. Consequently, the miniaturized high-power R/G/V/Y module mixed white-lighting OWC can reach a total data rate as high as 21.2 Gbps, which is much better than previous records ever reported. The frosted glass is used to uniformly diffuse the collimated glare laser light mixed by the R/G/V/Y source, which obtains a uniform spotlight with negligible dazzling and enlarged divergence. As a result, the divergent angle of the mixed white-light beam is expanded to $54^\circ$, which is

![Figure 15.](image)

**Figure 15.** Illuminance distribution of the miniaturized R/G/V/Y module mixed white-light source and a commercial car headlight. a) The illuminance distribution at different distances and b) the angle-dependent illuminance distribution of the miniaturized R/G/V/Y module mixed white-light source as compared to a commercial car headlight.

**Table 2.** Comparison of lighting performance.

|                           | Car headlight | Car headlight | RGVY-LD module |
|---------------------------|---------------|---------------|----------------|
|                           | low beam      | high beam     |                |
| CCT                       | 3000–7000 K   | 5176 K        |                |
| CRI                       | 60–80         | 60.7          |                |
| Divergence angle          | 80° (±40°)    | 30° (±15°)    | 54° (±27°)     |
| Illuminance (30 cm)       | 10 300 lux    | 45 300 lux    | 24 700 lux     |
| Illuminance (50 cm)       | 6400 lux      | 25 700 lux    | 12 800 lux     |
sufficient for serving as a high-beam headlight. The divergence can be further enlarged via the appropriate design of the lampshade to function as a low-beam headlight. After bias current optimization, the high-power R/G/V-LD module provides a total output power as high as 328 mW, which can provide an adequate illuminance for low-beam headlight with an illuminance of 12,800 lux over 0.5 m. The RGV-LD + Y-LED mixed white-lighting source has demonstrated a qualified CRI of 60.7, a standard cold white-light CCT of 5176 K, and the CIE coordinate at (0.3461, 0.4424) to serve as a car headlight for vehicle communication.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

color-rendering index, correlated color temperature, optical wireless communication, violet/green/red laser diodes, visible light communication, white lighting, yellow light-emitting diodes

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