All-in-one TO-can-Packed RGB-LD Lamp Enables 40-Gbit/s White-lighting Wireless DMT Link

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Abstract: White-lighting lamp beam with an all-in-one TO-can-packaged RGB-LD chip is performed with an illuminance of >300 lux, a CRI of >80, and a CCT of 6500K for free-space-optical wireless 16-QAM DMT link at 38.4 Gbit/s. © 2024 The Author(s)

1. Introduction

Free-space optical (FSO) data link is the last mile of the contemporary global wireless access network with full coverage of the whole space over the earth, which not only serves as the supplementary route but also guarantees the EM-wave immune security during data streaming and broadcasting. With combining versatile functionalities such as the lighting, projection, pointing, sensing and scanning, etc., such an FSO data link has gradually stepped into the society as a high value-added technology in the communication industry. The implementations of the FSO wireless local area network (LAN) with its channels spreading over different wavelength ranges have emerged since the end of last century. For example, the long-reach applications in near-infrared wavelengths including satellite-to-satellite, space-to-ground, and ground-to-ground links, the short-reach application in visible wavelengths such as the white-lighting, lidar sensing, smart house and industry 4.0 links. At early stage, only the near-infrared wavelength division multiplexing (WDM) scheme has been adapted to the FSO link due to the mature fabrication of the related LD sources. Recently, the visible WDM has also been comprehensively considered for various short-reach scenarios, as the scheme can extensively utilize the broadband carriers to exchange a very large amount of data transiently. However, the architecture of such a visible WDM FSO link usually requires a bulky geometrical optics for combining/separating different colored wavelength components at transmitting/receiving nodes, as the discrete colored LDs and PDs are individually packed within either the butterfly or the TO-can mounts for easily connecting with their driving circuits. Nevertheless, the total raw data rate of the WDM FSO with such kind of bulky and discrete LD modules can achieve higher than 34 Gbit/s by using precision geometric optics for beam collimation and separation [1-3]. Not long ago, the compact sub-modules of tri-/four-colored LDs with dichroic beam combiners were demonstrated for serving as white-lighting bulb or projector. With direct data encoding to each colored LD; however, the miniature visible WDM LD sub-module can only perform beyond 20-Gbit/s FSO transmission of advanced QAM-OFDM formatted data due to the imperfect optical design within a shrinking volume [4]. More recently, several new designs of the all-in-one TO-can package for combining the discrete red+green+blue tri-colored LD chips were announced. Owing to the identical sub-mounted package for all LD chips, such an all-in-one TO-can packed RGD-LD reveals a relatively collimated white-light beam without using additional optics. In this work, we demonstrate the use of such a specifically all-in-one TO-can packed RGB-LD to form the white-light lamp for WDM FSO wireless transmission with direct encoding by advanced discrete multitone (DMT) formatted data stream. Under the forward error correction (FEC) defined bit-error-ratio (BER) criterion, the qualified receiving and decoding of nearly 40-Gbit/s raw data are discussed in detail.

2. Experimental Setup

The discrete R/G/B-LD chips were provided by industrial partners after selecting from the commercially available products. The discrete R/G/B-LD chips were commonly grounded on the sub-mount indium-soldered to the holder of the TO-can housing. Both the N-type contact pad and P-type contact pad are gold-wire bonded to the cathode and anode pins, respectively. The whole TO-can package was surrounded by a hollow copper cube with a thermistor for thermal control, the copper cube was fixed upon a thermo-electric cooler (TEC) for stable heat transfer, and the TEC was plated on an aluminum heat sink with fan and cooling fins for long-term heat dissipation, as shown in Fig. 1(a). The cathode and anode pins of the all-in-one TO-can packed RGB-LD were further tin-soldered to the copper-plated coplanar transmission-lines printed upon an RF circuit board, in which three individual transmission lines were separately connected to the sub-miniature version A (SMA) connectors with -3dB bandwidth of better than 6 GHz. Then, the TO-can packed RGB-LD module was packaged into the lamp module as white-light source.

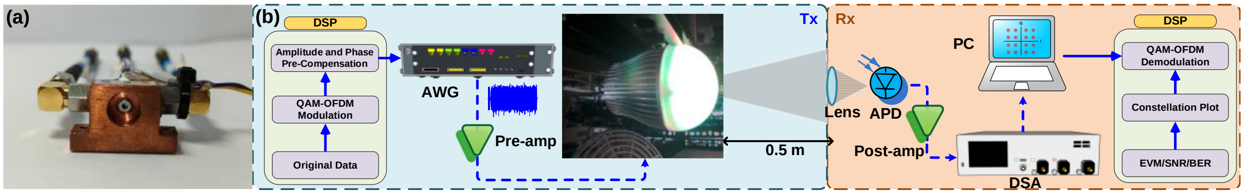

Fig. 1 (a) The photographs of the all-in-one TO-can packed RGB-LD transmitter. (b) The free-space optical wireless transmission system by the white-light lamp transmitter with the all-in-one TO-can-packaged RGB-LD.

After connecting each SMA to a corresponding semi-rigid cable assembly, each LD was DC-driven at the optimized bias of about 2.5 times the threshold condition, and directly encoded by the DMT data stream with a peak-to-peak amplitude of 1 V. Figure 1(b) shows the free-space optical wireless transmission system by the white-light lamp transmitter with the all-in-one TO-can-packaged RGB-LD. The DMT data stream was programmed via MATLAB with adding specialized algorithms and procedures. In general, each OFDM subcarrier in the DMT data stream carries the M-ary QAM data with M=16 mapped from the serial OOK data. After sending out the software-defined 16-QAM formatted data from PC to AWG, the DMT data stream was synthesized to perform the direct encoding of the RGB-LD through the bias-Tee with combining the DC bias. The back-to-back transmission was implemented using a single focusing lens for propagating through a desired distance in free space, then the white-light beam was refocused into the silicon p-i-n photodiode receiver for optical-to-electrical conversion and decoding. Afterwards, the waveform of the received DMT data stream was extracted and analyzed via the offline software-defined decoding program.

3. Result and Discussion

To flexibly adjust the CRI and CRI of such the white-light lamp output with all-in-one TO-can packed RGB-LD, and to optimize the direct modulation efficiency of each colored transmitter, the wavelength of the all-in-one TO-can packed RGB-LD are individually selected as 638-nm for red, 520-nm for green, 450-nm for blue, as shown in Fig. 2(a). In addition, both the P-I and V-I responses are analyzed to obtain the optimized bias current for each colored LD. All LDs are characterized with their bias of up to 3 times of the threshold current ($3I_{th}$) for protecting the device from damage under the air-cooled condition. Under this operating condition, the linewidth of the 638-nm, 520-nm, and 450-nm LDs are obtained as 4.5 nm, 5.8 nm, and 3.3 nm, respectively. The white-light lamp also exhibits the CRI >80 under the CCT of 6500 K at CIE coordinate of (0.31, 0.34), as shown in Fig. 2(a).

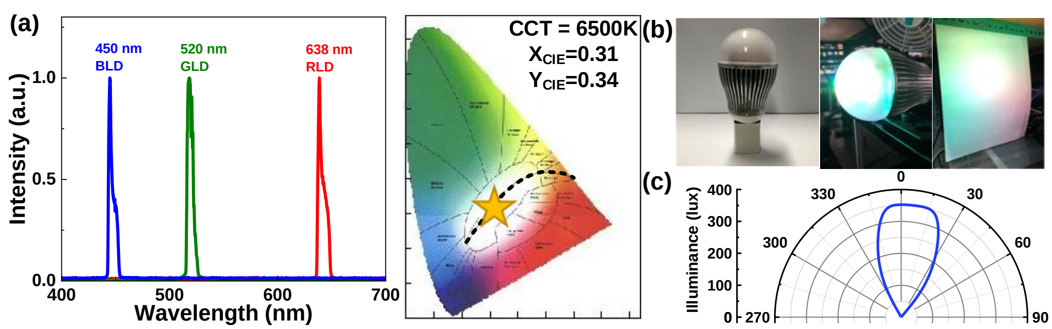

Fig. 2 (a) Optical and CIE spectra of the white-light lamp with the all-in-one TO-can-packaged RGB-LD. (b) The photographs of the white-light lamp with the all-in-one TO-can-packaged RGB-LD and its lighting spot on white paper. (c) The angle-dependent illuminance distribution of the white-light lamp with the all-in-one TO-can-packaged RGB-LD.

Figure 2(b) shows the spot obtained from the white-light lamp with the all-in-one TO-can-packaged RGB-LD. The laser beam of mixed white light illuminating on an A4 paper at a distance of 0.5 m exhibits uniform and clean white lighting spot without any dazzling speckle. To discuss the application possibility of the white-light lamp with the all-in-one TO-can-packaged RGB-LD, the angular distribution profile is shown in Fig. 2(c). At a distance of 50 cm, the illuminance of this white-light lamp achieves beyond 300 lux to satisfy the requirement of lighting levels from the Illuminating Engineering Society of North America (IESNA) [5]. From the angular distribution profile, the white-light lamp displays a divergent angle of >60° at 50 cm in horizontal axis. Although this white-light lamp exhibits a slightly high directionality, its divergent angle can be further increased by suitable defocusing design.

Under the $3I_{th}$ operation, the RLD exhibits the highest power of 60 mW with a power-to-current (P-I) slope efficiency ($\eta=\Delta P/\Delta I$) of 0.65 W/A and a differential resistance ($R_d=\Delta V/\Delta I$) of 10.1 Ω, as shown in Fig. 3(a). In Fig. 3(a), the GLD reveals its output power of 30 mW with the lowest slope efficiency of 0.43 W/A and a differential resistance of 17.1 Ω, whereas the BLD contributes the output power of 35 mW with the highest slope efficiency of 0.83 W/A and the largest differential resistance of 21.4 Ω. The lower signal reflection during the modulation associated with the higher modulation depth can be achieved if the differential resistance of the LD is closer to 50 ohms, indicating that the BLD exhibits the least energy consumption in both quantum emission and direct modulation efficiencies as compared to the RLD and GLD. Figure 3(b) shows the analog modulation frequency response of the all-in-one TO-can-packaged RGB-LD under the $3I_{th}$ operation. The -3-dB and -6-dB bandwidths of the RLD are observed as 2.85 GHz and 3.1 GHz. In addition, the related relaxation oscillation peak is obtained at 2.3 GHz. The frequency response of the GLD only exhibits the -3-dB and -6-dB bandwidths of 1.1 GHz and 1.25 GHz whereas the BLD shows -3 dB and -6 dB bandwidths of 1.2 GHz and 2.7 GHz.

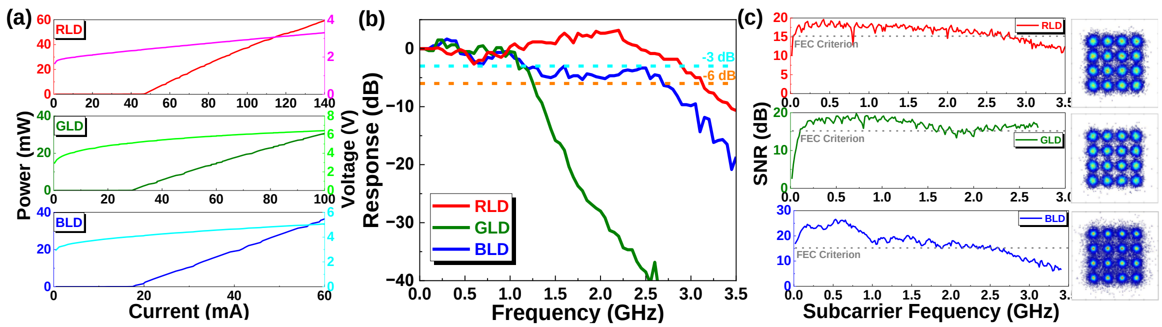

Fig. 3 (a) P-I and V-I curves of the all-in-one TO-can-packaged RGB-LD. (b) Frequency responses of the all-in-one TO-can-packaged RGB-LD under the 3-I_{th} operation. (c) The SNR spectra and constellation plot of the 16-QAM-DMT data carried by the white-light lamp with the all-in-one TO-can-packaged RGB-LD.

In principle, different digital encoding performances of the all-in-one TO-can-packaged RGB-LD in white-light lamp limited by the modulating bandwidth of the LD and the receiving responsivity of the PD are characterized. When employing the pre-compensated 16-QAM-DMT data format covering the usable bandwidth, the RLD shows a FEC-criterion qualified SNR (15.2 dB) spectrum covering a bandwidth of 2.7 GHz with only <-5dB decay when expanding the DMT subcarrier frequency to 3.5 GHz to obtain the average BER of 2.6×10^{-3}. The GLD reveals a notched SNR response at low-frequency region due to mode-partition noise originated from its multi-mode lasing feature, and its qualified modulation response can only extend to 2.7 GHz. In contrast, the BLD exhibits the largest fluctuation of up to 15 dB on its modulation throughput spectrum, leading to an FEC-qualified SNR at below 2.6 GHz accompanied with a 6-dB decay in SNR when extending the DMT subcarrier frequency to 3.4 GHz. After employing the amplitude and phase pre-compensating algorithm for the DMT data, the RLD can provide the largest allowable bandwidth of 3.5 GBaud for carrying the 16-QAM-DMT data stream at 14 Gbit/s, the GLD only offers 2.7 GBaud bandwidth for delivering the 16-QAM-DMT, and the B-LD delivers almost the same amount of 16-QAM-DMT data within 3.4 GBaud for 13.6 Gbit/s transmission. In this case, the white-light lamp with the all-in-one TO-can-packaged RGB-LD can provide total 38.4-Gbit/s 16-QAM-DMT data transmission.

4. Conclusion

The white-light lamp built by the discrete RGB-LDs with the all-in-one TO-can package is a newly proposed white-lighting source with miniatured opto-mechanic size and collimated beam output for specific towards the construction of a compact WDM FSO short-reach wireless data link and commercial display applications. The white-light lamp with the all-in-one TO-can-packaged RGB-LD also exhibits the CRI >80 under the CCT of 6500 K at CIE coordinate of (0.31, 0.34) and a divergent angle of 60°. This all-in-one TO-can RGB-LDs the transmitter can achieve the 16-QAM DMT data link at 38.4 Gbps. Such a white-light lamp with the all-in-one TO-can-packaged RGB-LD has opened a new era for such an ultra-miniature white-lighting WDM FSO transmitter to ultra-high-speed broadband short-reach data link.

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