Over 100Gbps Free-space Laser-based Visible Light Communication System Based on 10-λ WDM Module

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Abstract *We demonstrate a fully packaged 10-λ WDM integrated module based on visible light laser diodes. A data-rate of 110.79Gbps can be achieved in 17.5cm free-space and 1.5m fiber link. The experimental results show the potential applications in high-speed indoor access networks and data center interconnect.*

Introduction

As one of the new spectrum resources, visible light communication (VLC) has been widely studied in recent years because of its large available bandwidth and high transmission data rate [1, 2]. The application of wavelength division multiplexing (WDM) technology makes the transmission data rate of VLC system increase significantly [3]. The approach not only addresses the issue of spectrum resource scarcity by providing a new spectrum resource, but also holds promising potential for significantly reducing hardware costs. Tab.1 summarizes the recent advances in WDM-VLC systems [4-9]. To the best of our knowledge, the highest data rate achieved is 46.41 Gbps with 3~4 lasers integrated, which might not satisfy the growing demands in high-speed data links.

In this paper, we demonstrate a fully packaged 10-λ WDM integrated transmitter module based on 10 multi-mode fiber (MMF) coupled diode lasers. The MMF core diameter is 62.5 um. The emission wavelengths range from 405nm to 687nm, covering the entire visible spectrum. With DMT bit-power-loading modulation and Levin-Campello (LC) algorithm [10], a total data rate of 110.79 Gbps is achieved over 1.5 m multimode optical fiber and 17.5 cm of free space optical (FSO) link. The bit-error-rate (BER) of each channel satisfies the 7% hard decision forward error correction (HD-FEC) threshold of 3.8×10^{-3}. The research results provide a distinctive perspective and serve as a valuable reference for the development of high-speed data center interconnect (DCI) and indoor access networks aiming to achieve transmission rates at the terabits per second (Tbps) level.

Tab. 1: High speed LD based WDM-VLC systems recently.

Modulation	Tx	Data rate (Gbps)	Distance (m)	Year
QAM-OFDM [4]	RGB LDs	8.8	0.5	2017
DCO-OFDM [5]	RGBY LDs	35.6	4	2019
OFDM-bit-loading [6]	RGB LDs	40.665	2	2019
QAM-DMT [7]	RGBY LDs	34.8	0.3	2020
DMT-bit-loading [8]	RGB LDs	46.41	0.3	2022
DMT-bit-loading [9]	RGB LDs	11	0.1	2022

Experimental Setup

Fig.1 illustrates the high-speed WDM-VLC system, consisting of the transmitter module, cage system and receiver array. The transmitter module integrates the 12V DC power supply, temperature controllers, laser drivers, and multi-mode fiber-coupled diode lasers. The DC power

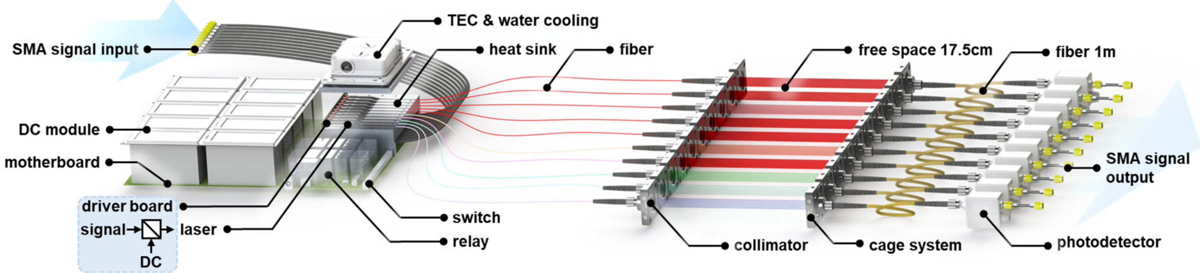

Fig. 1: The detail structure of high-speed WDM-VLC system with transmission module, cage system and receiver array.

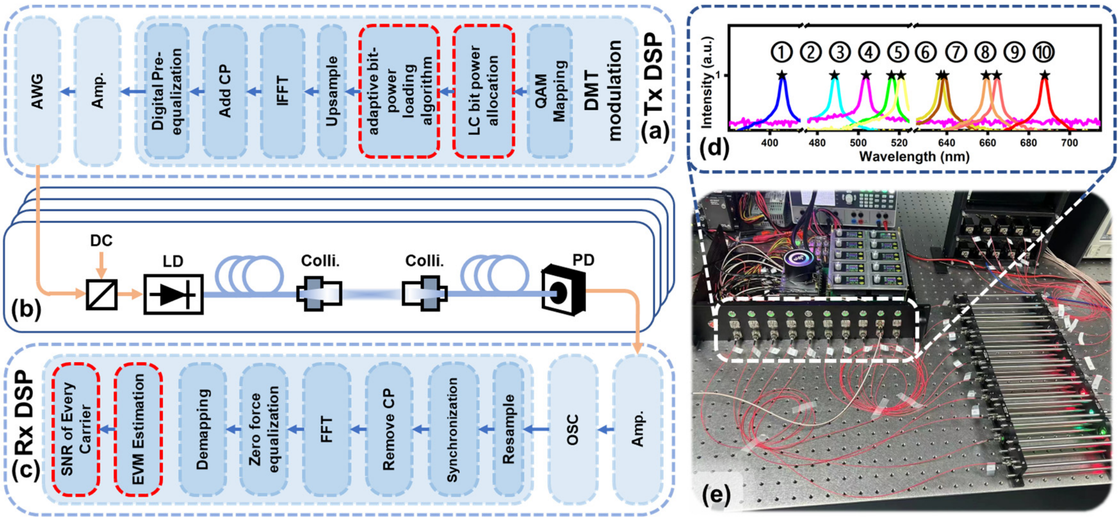

Fig. 2: The experimental setup and the spectrum of LDs; (a) Tx DSP; (b) system setup of one of the channels; (c) Rx DSP; (d) spectrum of ten LDs; (e) the photo of the system

supply module provides a suitable bias voltage for each laser to operate at an optimal operating point. The drive board located at the rear of the heat sink is designed to interface with the TO46-packaged 0.5m MMF coupled laser diodes with bias-Tee (RCBT-63+, Mini-Circuits). The electrical signal generated by the arbitrary waveform generator (AWG, M8190A, Keysight) is amplified by the amplifier (ZHL-1042J+, Mini-Circuits). As a proof-of-concept demonstration, the optical signal emitted is collimated and transmitted through a 17.5 cm free-space channel. At the receiver end, a Si photodetector (PD, DET025AFC, Thorlabs) with a 1 m multi-mode fiber (core diameter of 105 um) is used. An amplifier is connected to the PD and the received signal is collected by the oscilloscope (OSC, MSO9404A, Agilent Technology) for offline signal processing.

Fig.2(a)(b)(c) illustrates the digital signal processing (DSP) principle of the system, which adopts the DMT bit power loading algorithm and combines it with digital pre-equalization algorithm. The system estimates the signal-to-noise ratio (SNR) of each communication link by sending 4QAM signals, and then utilized the LC allocation algorithm to allocate the maximum order that each subcarrier can carry, as shown in Fig.2(a). Finally, the system sends QAM signals modulated by DMT and bit power loading, and the spectrum of the signal transmitted by AWG and received by OSC is shown in Fig.2(c). The photo of the demonstrated system is presented in Fig.2(e).

Experimental Result

Fig. 2(d) depicts the emission spectra of the 10-λ WDM integrated laser transmitter. The peak emission wavelengths are 405nm, 488nm, 505nm, 516nm, 520nm, 637nm, 639nm, 659nm, 664nm, 687nm, covering a wide range of visible bands. The frequency response of laser transmitter is studied by measuring the S_{21} parameter using vector network analyzer (VNA, SVA1032X, Siglent). The corresponding -20dB modulation bandwidths are 1.79GHz, 1.72GHz, 1.85GHz, 1.4GHz, 1.47GHz, 2.95GHz, 1.85GHz, 1.81GHz, 1.85 GHz, and 2.34GHz respectively.

In this study, the appropriate operating conditions for each laser diode (LD) were determined by measuring the estimated data rate (R_b) as a function of bias current (I_d) and signal peak-to-peak voltage (V_{pp}) using the bit-power loading scheme with a bit-error rate (BER) threshold of 3.8×10^{-3}. The results, presented in Fig.3, show the R_b contours at a signal bandwidth of 2GHz for each of the ten LD channels. It was found that the performance of the system was affected by the combination of I_d and V_{pp}. The estimated data rate initially increased as V_{pp} increased when I_d was fixed, due to the enhanced signal power resulting in a higher SNR. However, as V_{pp} continued to increase, the nonlinearity of the system became stronger, resulting in a decrease in R_b. Thus, there was a tradeoff between SNR and nonlinearity, and an optimal combination of I_d and V_{pp} was identified for each LD channel.

The areas of data rate above a certain value are circled with black lines, and the optimal operating points are marked with an asterisk in Fig.3(a)-(j) for ten LD channels, respectively. For example, the area where data rate exceeds 11.61Gbps is circled for the first LD channel (405 nm) in Fig.3(a), and the operating point is located at 110mA bias current (I_d) and 300mV signal V_{pp}. In this way, we can ensure that each LD channel is in best condition.

The highest achievable data rate of each LD channel is summarized in Tab.2. The 516 nm LD

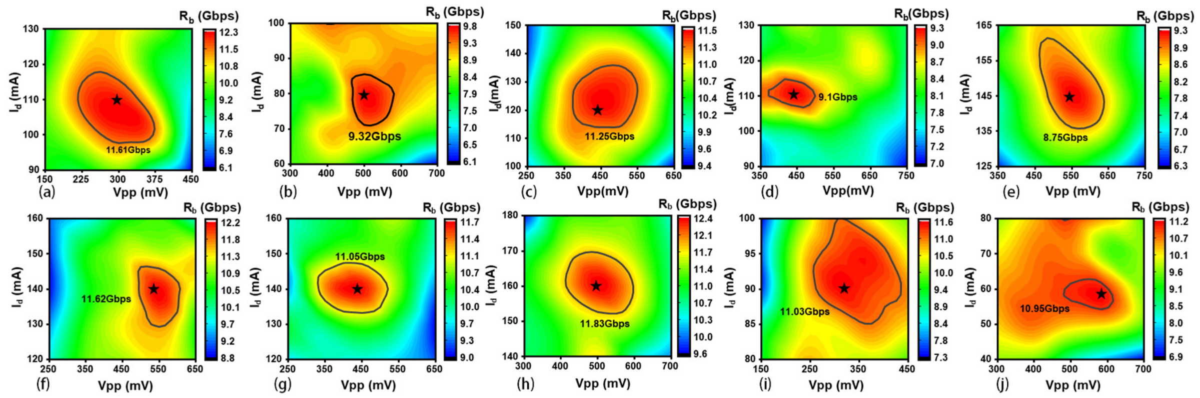

Fig. 3: The data rate R_b of ten channels at all operating points. The R_b contours of (a) 405nm, (b) 488nm, (c) 505nm, (d) 516nm, (e) 520nm, (f) 637nm, (g) 639nm, (h) 659nm, (i) 664nm, (j) 687nm.

channel has a minimum achievable data rate of 9.28Gbps, and the 659nm LD channel has the maximum achievable data rate of 12.41Gbps. These ten WDM LD channels achieve a total data rate of 110.79Gbps.

Tab. 2: The data rate of ten optical-fiber channels

λ (nm)	Data rate (Gbps)	BER
405	12.16	0.00208
488	9.73	0.00346
505	11.49	0.00339
516	9.28	0.00197
520	9.30	0.00342
637	12.16	0.00340
639	11.69	0.00362
659	12.41	0.00329
664	11.47	0.00239
687	11.00	0.00072
Total rate	110.79 Gbps	

To further illustrate the bit-power loading algorithm, SNR response and the details of bit-power loading are given in Fig.4. Fig.4(a)-(c) shows the SNR response of the transmission system and allocated bit numbers for 488 nm, 520 nm, and 637 nm LD channels, respectively. According to the bit-power loading algorithm, the channel information can be estimated by transmitting test sequences. From Fig.4(a)-(c), the high-frequency fading of the SNR response can be clearly seen, which results from the bandwidth limitation of the device. Higher signal-to-noise ratio can support higher-order signal transmission, so larger bit numbers are allocated in frequency components with a higher SNR condition. In Fig.4(a)-(c), the allocated bit numbers vary from 2 to 7, which correspond to 4QAM to 128QAM signal modulation. The constellation points at the receiving end have also been shown in the insets. In addition to loading signals of different orders, the transmitted signal energy at different frequency components should also be adjusted accordingly to maximize the utilization of channel resources. Fig.4(d) (I)-(III) display the distribution of transmitted signal power for 488 nm, 520 nm, and 637 nm LD channels, respectively.

Conclusions

We have demonstrated a fully packaged 10-λ WDM integrated module based on 10 multi-mode fiber-coupled diode lasers. Utilizing the fully packaged 10-λ WDM transmitter, a combined data transmission rate of 110.79 Gbps has been achieved through 17.5cm free-space and 1.5m MMF channel. The experimental results cast lights on the potential application of laser VLC systems in high-speed indoor access networks and DCI.

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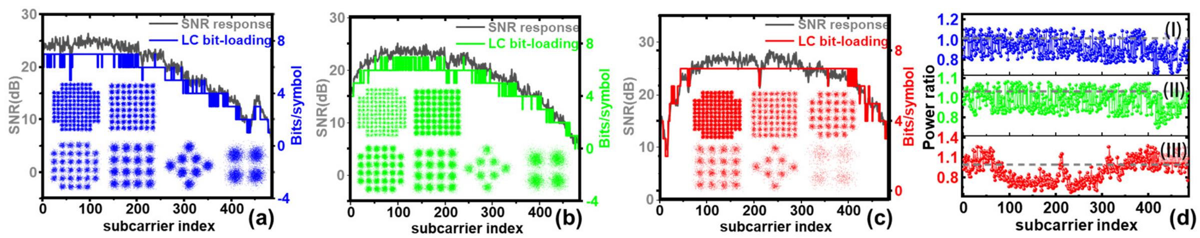

Fig. 4: SNR response and LC bit-loading allocation results for (a) 488nm LD channel, (b) 520nm LD channel, (c) 637nm LD channel; (d) The distribution of transmitted signal power for (I) 488 nm, (II) 520 nm, and (III) 637 nm LD channels.

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