20.09-Gbit/s Underwater WDM-VLC Transmission based on a single Si/GaAs-substrate Multichromatic LED array chip

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Abstract: We demonstrated a record-breaking 20.09-Gbit/s WDM-VLC transmission over 1.2 m underwater link with PS-bitloading-DMT modulation. A silicon-substrate multichromatic LED array chip and a feasible optical-filter scheme are proposed for future LED-based WDM-VLC system.

1. Introduction

Ever-increasing global climate change and resource depletion have aroused growing interest for the research of underwater exploration, which highly demanding for high-capacity underwater communication [1]. For the existing underwater communication technology such as radio-frequency (RF) and acoustic communication, the high attention of RF and the low bandwidth (2-5kHz) of acoustic signal in seawater severely limit their further application for future high-speed and long-distance underwater communication. Consequently, underwater optical wireless communication (UOWC), especially underwater visible light communication (UVLC), attracts more attention because of the relatively low attenuation optical window of the blue-green-yellow light for seawater, and its potential for beyond Gbit/s-class information transmission [2].

In UVLC system, laser diodes (LDs) has been demonstrated the feasibility to construct a Gbit/s visible light communication (VLC) link [3]. However, the issue of eye-safety and speckle effect of LDs cannot be neglected, while its modulation bandwidth is wider than light-emitting diodes (LEDs). Hence, LED-based UVLC system is gradually developing with the advantages of low-cost, easy-alignment and Gbps-class transmission capacity. Though a single-color LED already has the capacity to realize around 3-Gbit/s VLC [4], Wavelength-Division-Multiplexed (WDM)-VLC is another promising technology to accomplish beyond 10-Gbit/s data rate VLC system, where multi-color LEDs are combined to modulate different signal sequences independently. Besides, a vast majority of the beyond-8-Gbps WDM-VLC transmission has been demonstrated [5-10], listed in Fig.1 (a). Nevertheless, the utilized number of LED color in these works is only up to 5. In addition, the low output optical power of the μLED in Ref. [5] restrains its transmission distance for a long-distance underwater link. Thus, much progress for the higher transmission capacity of a UVLC system is expected if an emitter with more than 5-color LED and a feasible optical-filter scheme can be realized. To maximum the spectral efficiency (SE), probabilistic shaping (PS) is an emerging cutting-edge constellation shaping technology which can combine with DMT to narrow the gap between the current SE and Shannon limit [11].

In this paper, we propose a self-designed Si/GaAs-substrate multichromatic LED array chip for a beyond 20 Gbit/s UVLC system, which is embedded 4 X 4 LED array with different light wavelengths distributed in the visible-

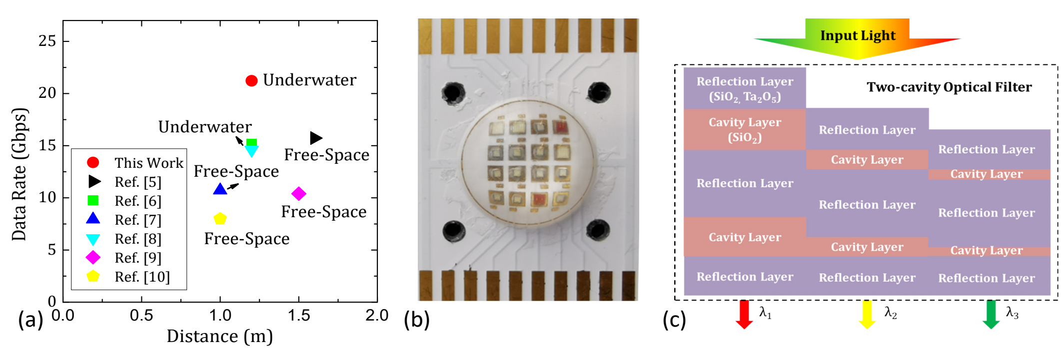

Fig. 1. (a) Recent work comparison for WDM-VLC Transmission. (b)The image of the packaged LED array chip with 16 colors. (c) The scheme of the two-cavity optical filter for WDM-VLC system (An example for 3 filtered wavelengths).

light spectrum. By utilizing 8 of all LEDs as our transmission channels, an achievable information rate (AIR) of 20.09-Gbit/s UVLC transmission over 1.2-m pure water link is demonstrated with probabilistic-shaping (PS)-bitloading-DMT modulation. Besides, a feasible two-cavity optical filter scheme is also proposed for separating each channel. To the best of our knowledge, it is the highest data rate for LED-based UVLC transmission.

2. Devices and Experimental setup

The image of the packaged LED chip with 20 pin and 16 LEDs is shown in Fig.1 (b). Exploiting the unique properties of Si substrate consisting of low-cost, large substrate size, and high crystal quality and so on, every GaN/GaP-based high-brightness LED is grown on patterned Si(111)/GaAs substrates by home-made metal organic chemical vapor deposition (MOCVD) system according to Ref [12]. The 4 X 4 LED array is packaged in one LED lamp with wavelength range from 456 nm to 660 nm. To minimum the possible channel crosstalk, the wavelength of 456 nm, 480 nm, 500 nm, 526 nm, 556 nm,583 nm, 631 nm and 660 nm are employed for our UVLC transmission.

Fig.1 (c) illuminates the schematic of the proposed two-cavity optical filter used for separating the received light into several individual output lights with desired central wavelength. Its structure mainly includes multilayer films deposited alternatively by Ta_2O_5 and SiO_2. The accurate wavelength of the filtered light can be tuned by continuously changing the thickness of the cavity layer. In addition, several cascaded multiple short-wavelength pass cut-off films are used to broaden the stopband effectively to restrain the channel crosstalk [13].

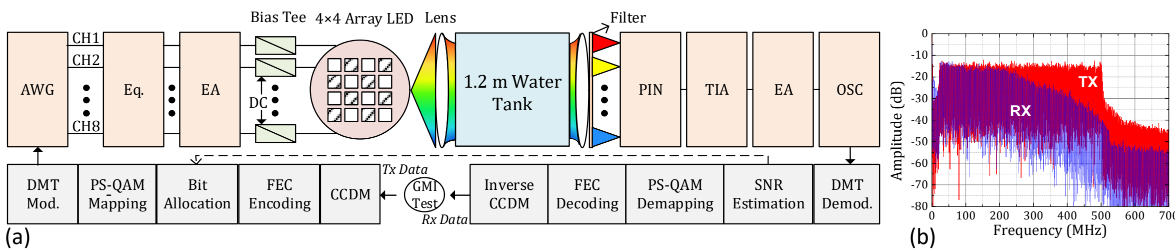

Fig. 2. (a) The experimental setup and the flow diagram of signal generation and offline processing. (b) The frequency response of transmitted signal (Tx) and received signal (Rx).

The UVLC system is established by placing the proposed LED at a distance of 1.2 m from a commercial PIN (HAMAMATSU S6968), shown in Fig.2 (a). First, 8 channels of PS-bitloading-DMT signals are generated by an arbitrary waveform generator (AWG, Tektronix, AWG710b). After hardware equalization and amplification, these 8 channels of signal are respectively modulated on 8 selected LEDs. At last, the signal detected from PIN is amplified by trans-impedance amplifier (TIA) and electro-amplifier (EA), then fed into an oscilloscope (Agilent, MSO9254A) for offline processing. Fig.2 (b) is the frequency response of the transmitted signal (TX) and received signal (RX) revealing the severe attenuation of UVLC system induced by devices and the complex channel.

PS-bitloading-DMT modulation is proposed to maximum the spectral efficiency of our UVLC system. A constant composition distribution matching (CCDM) and a forward error correction (FEC) decoder are utilized to generate I- and Q-path PS-PAM-16 with the optimal Maxwell-Boltzmann (MB) distribution based on the SNR of every DMT subcarriers. These generated PS-PAM-16 signals produce corresponding PS-QAM-128 constellation with a certain entropy. In this way, every subcarriers' spectral efficiency can be closed to the Shannon limit. Besides, the AIR can be calculated by the generalized mutual information (GMI) and binary FEC code rate of 0.9 in our work according to the equation (3) in [14]. All value of AIR in this work are removed the 11.11 % FEC overhead.

3. Results and Discussion

First, we measured the best working current and peak-to-peak voltage (Vpp) of every LEDs to get the best transmission performance for UVLC system listed in Table 1. Based on these optimal working points, the corresponding output power is also tested and listed in Table 1. From the results, the output power of blue-green light stays the most portion of the total output power allowing this LED for high-speed UVLC transmission. To further explain the characteristics of the utilized 8 channels of LEDs, the Commission Internationale de l'Eclairage (CIE) chromaticity coordinates and the normalized optical spectrum of every LED illustrate the accurate central wavelength and the color of the 8 LEDs in Fig.3 (a-b). It's obvious that the spectrum of the adjacent channel slightly overlaps each other due to the LED's wide emission spectrum.

In order to eliminate the channel crosstalk and separate every channel at the receiver, 8 kinds of two-cavity optical filters are well designed with 8 different pass-band and wide stop-band. Comparing to the spectrum of the LED (Fig.3 (b)), optical filter's pass-band are precisely located at the central wavelength point of the transmitted light.

Compromising between ICI and received light power, the full width half maximum (FWHM) and transmission of every pass-band are the key paraments which are respectively set to around 10 nm and higher than -4 dB in Fig.3 (c).

Table 1. The optimal working current, Vpp, output power, and the highest AIR for every chip of LED

	456 nm	480 nm	500 nm	526 nm	556 nm	583 nm	631 nm	660 nm
Current (mA)	160	260	280	260	340	400	180	260
Vpp (V)	1	1.1	1.3	1.2	1.5	1.6	1	0.9
Output Power (mW)	40.4	55.6	68.6	47.4	21.2	17.8	24.4	10.1
Highest AIR (Gbps)	2.88	2.84	2.74	2.40	1.76	1.44	2.78	3.16

In the end, we measured the AIR of every LED under different modulation bandwidth. The results, shown in Fig.3 (d) and Table 1, indicates that the WDM-UVLC system can totally achieve an AIR of 20.09Gbit/s with 8 WDM channel after removing the FEC coding redundancy. The constellation diagram of the received signal with the highest AIR are shown in Fig.3 (e-l). To verify a rate-0.9 can produce error-free post-FEC results for our UVLC transmission, the minimum NGMI among every frequency subcarriers of the highest data-rate signal point is calculated and its value is higher than 0.9 for every chip (Fig.3 (m)).

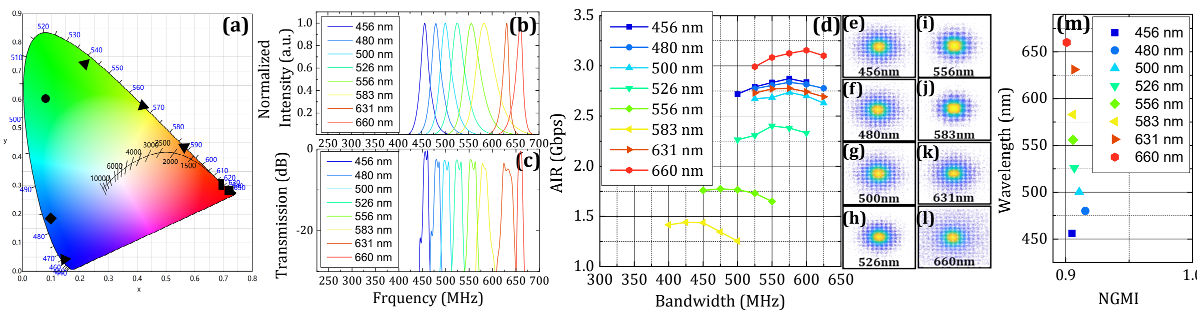

Fig.3 (a) CIE diagram showing the chromaticity coordinates of the 8 kinds of chips in the proposed LED. (b) EL spectra for the utilized 8 kinds of chips. (c) The transmission spectrum of the proposed optical filter. (d) The AIR with different signal bandwidth for different chips. (e-l) The corresponding constellation diagram of the highest AIR signal points for different chips. (m) The minimum NGMI among every frequency subcarrier for different chips.

4. Conclusion

A Si/GaAs-substrate multichromatic 4Ⅹ4 LED array chip and a feasible two-cavity optical filter are proposed for future WDM-UVLC transmission. We experimentally demonstrated an AIR of 20.09 Gbit/s UVLC transmission with the PS-bitloading-DMT modulation based on the proposed LED. The results highly validate the potential of Si/GaAs-substrate LED for future high-capacity WDM-UVLC.

Acknowledgements

This work was partly supported in part by the National Key Research, Development Program of China (2017YFB0403603), and the NSFC project (No.61571133).

5. References

[1] Z. Zeng et al., IEEE Communications Surveys & Tutorials, vol. 19, no. 1, (2016).
[2] N. Chi *et al.*, *Optics express,* vol. 26, no. 20 (2018).
[3] H. M. Oubei *et al.*, *Optics express,* vol. 23, no. 16 (2015).
[4] F. Wang *et al.*, *Optical Engineering,* vol. 58, no. 5 (2019).
[5] R. Bian *et al.*, *Journal of Lightwave Technology,* vol. 37, no. 10 (2019).
[6] Y. Zhou *et al.*, *Photon. Res.,* vol. 7, no. 9 (2019).
[7] X. Zhu *et al.*, in *Optical Fiber Communication Conference*, (2018).
[8] J. Shi *et al.*, in *2019 Optical Fiber Communications Conference and Exhibition (OFC)* (2019).
[9] H. Chun *et al.*, *Journal of lightwave technology,* vol. 34, no. 13 (2016).
[10] Y. Wang *et al.*, *IEEE Photonics Journal,* vol. 7, no. 6 (2015).
[11] C. Xie *et al.*, *Optics express,* vol. 26, no. 1 (2018).
[12] C. Xiong *et al.*, *Science in China Series E,* vol. 49, no. 3, 2006.
[13] S.-W. Wang *et al.*, *IEEE wireless communications,* vol. 22, no. 2 (2015).
[14] J. Cho *et al.*, in *2017 European Conference on Optical Communication (ECOC)*, (2017).