Capacity Enhancement of VLC by Blue-green Wavelength Division Multiplexing Using Optical Phased Array

Yujie Di [1,2], Caiming Sun [2,3], Shuyan Chen [1], Weiwei Liu [2], Yizhan Dai [1], Binghui Li [3], Wu Shi [2], Jing Lin [2], Yingjie Shao [4], Jing Xu [5], and Lian-Kuan Chen [1]

[1]*Department of Information Engineering, The Chinese University of Hong Kong, Hong Kong SAR, China*
[2]*Peng Cheng Laboratory (PCL), Shenzhen 518055, Guangdong, China*
[3]*Shenzhen Institute of Artificial Intelligence and Robotics for Society (AIRS), The Chinese University of Hong Kong (CUHK), Shenzhen, China*
[4]*Centre for Applied Photonics Fraunhofer UK Research Ltd, Glasgow, U.K.*
[5]*Optical Communications Laboratory, Ocean College, Zhejiang University, Zheda Road 1, Zhoushan, Zhejiang 316021, China*
Author e-mail address: dy019@ie.cuhk.edu.hk

Abstract: We proposed and experimentally demonstrated the first blue-green OPA-based WDM-VLC systems with narrow channel spacing. A 4.5-Gbit/s transmission with 50% capacity enhancement was achieved by OCT-precoding and simplified third-order Volterra equalization.

1. Introduction

Due to the proliferation of subsea resource exploration, a high-speed and robust underwater communication system is needed for data transmission between underwater vehicles and the base station [1]. Optical wireless communication (OWC) using blue-green light is a promising candidate for short- and medium-range underwater communication for its high bandwidth and moderate attenuation compared to acoustic and RF signals, respectively [2]. To markedly boost system capacity, wavelength division multiplexing (WDM) has been widely employed in fiber-optic communication systems. WDM has also been applied to free-space optical communication (FSO) and visible light communication (VLC) systems. FSO utilizes mature infrared light for WDM systems [3]. Current WDM-VLC systems often use red, green, and blue wavelengths with wide channel spacing, thus limiting the available wavelength channels [4][5]. It is partly due to the lack of multi/demultiplexers with fine wavelength spacing for visible light. An optical phased array (OPA) can be used for wavelength demultiplexing as different wavelengths are deflected with different angles [6][7]. OPA facilitates high channel-count WDM systems as it could demultiplex channels with narrower wavelength spacing. In this paper, we experimentally demonstrated a blue-green OPA-based WDM system with a wavelength spacing as small as 4 nm. The communication performance was investigated, and advanced digital signal processing (DSP) schemes were employed to achieve capacity enhancement. A 4.5-Gbit/s WDM transmission with 50% capacity enhancement was realized using a simplified third-order Volterra equalization and orthogonal circulant matrix transform (OCT) precoding.

2. Principle of the blue-green OPA-based VLC-WDM system

In the system, multiwavelength channels are data-modulated and combined. Then an OPA is used to deflect different wavelength signals with different angles. The deflection angle is characterized by $sin\theta = n_{eff} - \lambda/\Lambda$, where n_{eff} is the effective refractive index of the guided mode, λ is the light wavelength, Λ is the grating period. θ is the angle between the output beam and the direction perpendicular to the chip [6][7]. After a free space distance d, the position of the light spot relative to the center point can be calculated by $l = d \times tan\theta = d \times tan\,(arcsin\,(n_{eff} - \lambda/\Lambda))$. The spacing between two adjacent wavelength channels can then be derived. Narrower wavelength spacing in WDM transmission offers an increased channel count, at the expense of deteriorated channel crosstalks; thus, the wavelength spacing when OPA is used for demultiplexing needs to be optimized. After the detection, a low-complexity third-order Volterra equalizer is employed to compensate for intersymbol interference (ISI) and nonlinearity [8]. The simplified Volterra model only includes the 1st-order, 2nd-order, and diagonal 3rd-order terms and is expressed as:

$$\hat{d}(n) = \sum_{m_1=0}^{M_1-1} w_1(m_1)x(n-m_1) + \sum_{m_{21}=0}^{M_2-1}\sum_{m_{22}=m_{21}}^{M_2-1} w_2(m_{21},m_{22})x(n-m_{21})x(n-m_{22}) + \sum_{m_3=0}^{M_3-1} w_3(m_3)x^3(n-m_3). \quad (1)$$

where $\hat{d}(n)$ and $x(n)$ are the equalizer output and received signal at time n, respectively, $w_k(\cdot)$ is the coefficient of a kth-order kernel, and M_k is the memory length of the kth-order kernels. After the equalization, the data is recovered, and the bit-error rate (BER) is derived for each channel.

3. Experimental setup and results

The experimental setup of the proposed OPA-based WDM system is shown in Fig. 1(a). Input lights from four pigtail laser diodes (LDs) with wavelengths of 492 nm, 506 nm, 518 nm, and 522 nm are combined via a 1×4 coupler (Thorlabs, TWQ560HA). The radio frequency (RF) signals were generated from an arbitrary waveform generator (AWG, SDG7102A, 1-GHz bandwidth). A direct current (DC) bias was superimposed on the RF signal via a bias tee (Mini-Circuits, ZFBT-4R2GW+), and the combined signals were applied to modulate the LDs. The signal's amplitude and bias voltages were optimized for BER performance. Fig. 2(a) and 2(b) show the four LDs' optical spectrum and normalized frequency responses. After the four combined wavelengths were demultiplexed by an OPA, a cylindrical lens with a focal length of 15 cm was used to concentrate the light spot. The light spots before and after the cylindrical lens are shown in Fig. 1(b) and 1(c). The signals were then detected by a photomultiplier tube (PMT, Hamamatsu H14447), followed by a trans-impedance amplifier (TIA, Hamamatsu C5594). At last, the signals were captured by an oscilloscope (Keysight, DSOX6004A) for further offline processing. During the BER measurement of a channel, the channel and its adjacent channel with a narrower wavelength spacing were loaded with different modulated signals at the same sampling rate. The remaining two wavelength channels were in CW mode. We turned on and off the remaining channels to investigate the crosstalk to a particular channel, and negligible BER degradation was observed. The received optical powers were 140 nW, 712 nW, 316 nW, and 239 nW at 492 nm, 506 nm, 518 nm, and 522 nm, respectively. The loss was mainly due to the coupler and the OPA prototype for this WDM demonstration. One hundred packets were collected for data analysis under different data rates and modulation formats. Each packet contained 16383 symbols for On-Off Keying (OOK) or 32640 symbols for DC-biased orthogonal frequency division multiplexing (DCO-OFDM) modulation.

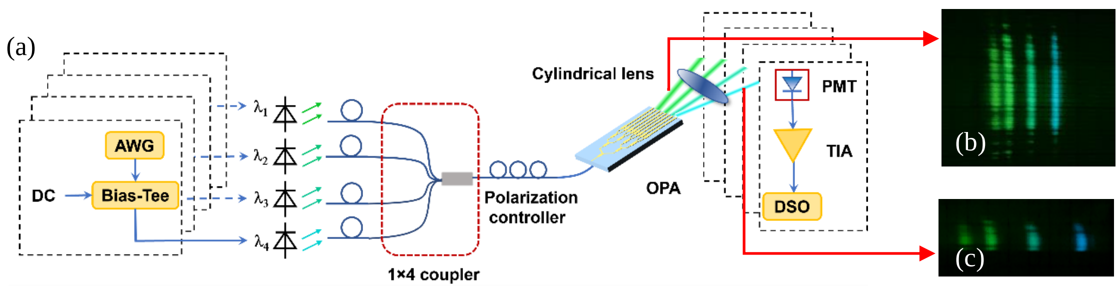

Fig. 1. (a) Experimental setup of OPA-based WDM system, (b) light spots before the cylindrical lens, and (c) light spots after the cylindrical lens.

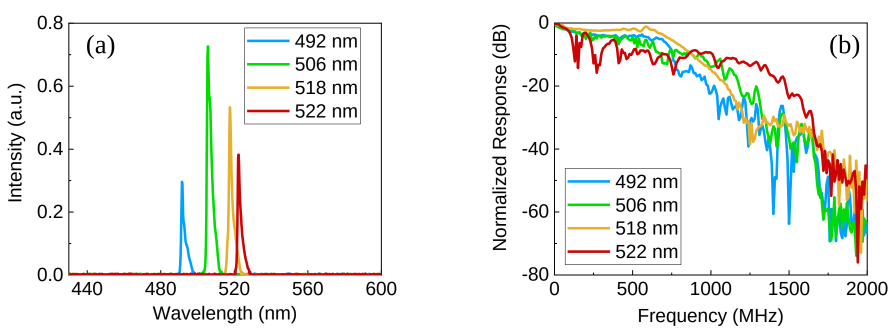

Fig. 2. (a) Optical spectra and (b) normalized frequency responses of four LDs with different wavelengths.

In this paper, M_1, M_2, and M_3 of the Volterra equalizer were optimized for different data rates in OOK modulation and OFDM modulation. One thousand symbols for OOK modulation and 2,000 symbols for OFDM modulation were used as the training symbols to estimate $w_k(\cdot)$. The four wavelengths' BERs under OOK modulation are shown in Fig. 3(a) and 3(b). With the applied Volterra equalization, the data rate can be improved from 1.8 Gbit/s to 3.5 Gbit/s at BER = 2.0×10^{-2} (SD-FEC threshold) for OOK modulation. The number of lasers and their wavelength spacing were limited by the available lasers in our labs, and system capacity could be enhanced with additional lasers.

To further maximize the system capacity, we employed DCO-OFDM for the 506-nm LD, as it exhibited the highest output power and the best BER performance under OOK modulation. IFFT was conducted after serial-to-parallel (S/P) conversion and 8-quadrature amplitude modulation (QAM) mapping. The cyclic prefix (CP) length was 1/8 of one OFDM symbol, and 255 out of 512 subcarriers were modulated with data for each OFDM symbol. Due to the uneven SNR distribution of the subcarrier, OCT precoding was applied to optimize the BER performance [9]. The QAMmapped signal was multiplied by an orthogonal circulant matrix, and the signal was recovered at the receiver by multiplying the inverse OCT matrix. As expected, the OCT-precoding OFDM scheme outperformed the conventional OFDM scheme. The performance was improved further with the Volterra equalization. Overall, the data rate was improved from 3 Gbit/s to 4.5 Gbit/s at BER = 2.0×10^{-2}, achieving a 50% capacity enhancement.

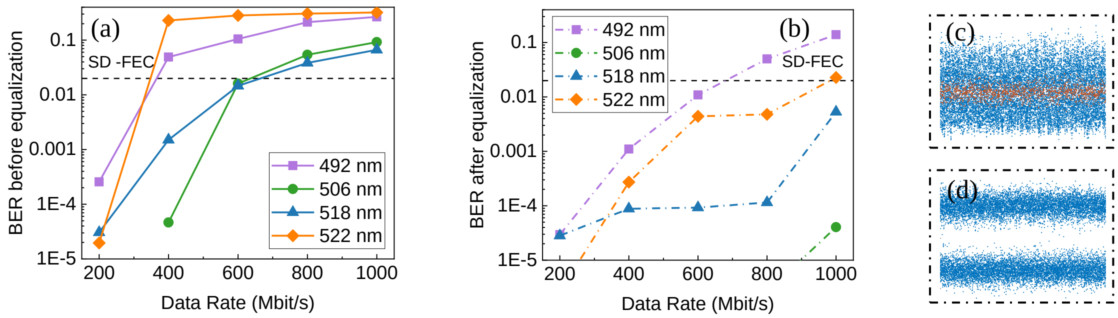

Fig. 3. BER versus different data rates for OOK modulation (a) before Volterra equalization and (b) after Volterra equalization. Signal amplitude distributions of 506 nm at 1-Gbit/s sample rate (c) before Volterra equalization and (d) after Volterra equalization.

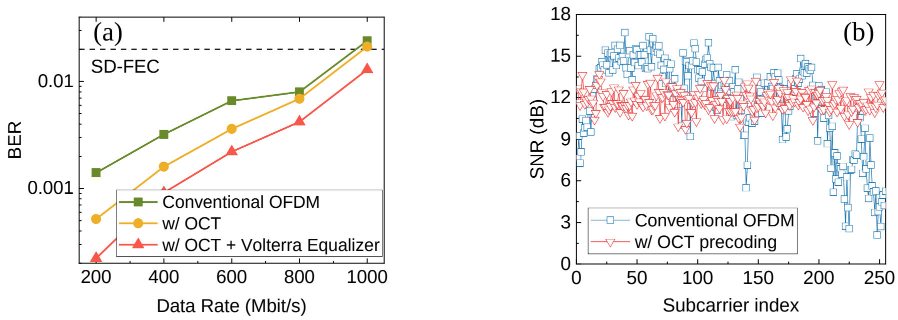

Fig. 4. (a) BER versus data rate for 8QAM-OFDM modulation, and (b) SNR profiles of the using conventional OFDM and OCT precoding at 1 GSa/s for 506 nm.

4. Conclusion

In summary, we realized a blue-green WDM-VLC system using an OPA with narrow channel spacings to boost the system capacity in a proof-of-concept demonstration. By using a simplified third-order Volterra equalization and OCT precoding, the data rate can be improved from 3 Gbit/s to 4.5 Gbit/s at BER = 2.0×10^{-2}, showing a 50% capacity enhancement. The experimental results validate the potential of OPA for future high-capacity WDM-UOWC. The superior beam steering ability of OPA will be investigated in the future for beam wandering compensation to realize robust and high-speed UOWC systems. This work is supported in part by HKSAR RGC GRF 14207220, 14204921, National Natural Science Foundation of China (62175120, 62005181), Guangdong Basic and Applied Basic Research Foundation (2021B1515120084), and Tip-top Scientific and Technical Innovative Youth Talents of Guangdong Special Support Program (2019TQ05X062).

5. References

[1] L. -K. Chen, Y. Shao and Y. Di, "Underwater and Water-Air Optical Wireless Communication," *IEEE J. Lightwave Technol.*, vol. 40, no. 5, pp. 1440-1452, 2022.

[2] Sun X *et al.*, "A review on practical considerations and solutions in underwater wireless optical communication." *IEEE J. Lightwave Technol.*, vol. 38, no. 2, pp. 421-431, 2020.

[3] E. Ciaramella, *et al.*, "1.28 terabit/s (32x40 Gbit/s) wdm transmission system for free space optical communications," *IEEE J. Sel. Areas Commun.*, vol. 27, no. 9, pp. 1639-1645, 2009.

[4] Wen-Yi Lin *et al.*, "10m/500Mbps WDM visible light communication systems," *Opt. Express*, vol. 20, no.9, pp. 9919-9924, 2012.

[5] F. Hu *et al.*, "20.09-Gbit/s Underwater WDM-VLC Transmission based on a single Si/GaAs-substrate Multichromatic LED array chip," in *Proc. OFC*, San Diego, USA, 2020, paper M3I.4.

[6] C. Sun *et al.*, "Large-Scale and Broadband Silicon Nitride Optical Phased Arrays," *IEEE J. Sel. Top. Quantum Electron*. Vol. 28, no. 6, pp. 1-10, 2022.

[7] C. Sun *et al.*, "Parallel emitted silicon nitride nanophotonic phased arrays for two-dimensional beam steering," *Opt. Lett.*, vol. 46, no. 22, pp.5699-5702, 2021.

[8] Dai Y *et al.*, "200-m/500-Mbps underwater wireless optical communication system utilizing a sparse nonlinear equalizer with a variable step size generalized orthogonal matching pursuit." *Opt. Express*, vol. 29, no. 20, pp.32228-32243, 2021.

[9] Y. Hong and L.-K. Chen, "Toward user mobility for OFDM-based visible light communications," *Opt. Lett*., vol. 41, no. 16, pp. 3763–3766, 2016.