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[a]Fujian University of Technology, School of Information Science and Engineering, Fujian, China
[b]National Taipei University of Technology, Institute of Electro-Optical Engineering, Taipei, Taiwan

Abstract. An underwater wireless red-light laser transmission system using 10-Gbps 16-quadrature amplitude modulation–orthogonal frequency-division multiplexing (OFDM) modulation based on a high-speed multimode 680-nm vertical-cavity surface-emitting laser (VCSEL) was proposed and demonstrated. This study is the first attempt to adopt red light for transmitting a 10-Gbps wireless signal 6-m underwater. With the adoption of the appropriate OFDM base bandwidth and modulation parameters after studying the frequency characteristics of the high speed multimode 680-nm VCSEL and contrast experiment of modulation parameters, a good bit error rate performance and clear constellation maps are achieved. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.OE.57.6.066110]

1 Introduction

In the past, underwater wireless laser transmission systems adopted a 405-nm blue-laser light for underwater transmission, which has minimum attenuation in clear water.[1–5] Compared with blue-laser light, the absorption rate of red-laser light in clear water is higher, resulting in a shorter transmission distance. However, red laser has a significantly wider frequency response at a much lower price and, thus, provides a considerably wider transmission bandwidth. In addition, in terms of the photodiode (PD), the receiving sensitivity of the 620- to 750-nm red-light bandwidth is far higher than that of the 380- to 495-nm blue-light bandwidth.[6] Moreover, considerable research on underwater wireless light communication has been conducted in recent years. A study on underwater transmission characteristics, attenuation coefficient, and channel bandwidth regarding blue, green, and red lights had been proposed,[7–8] from which an interesting finding was obtained—red light has a better transmission performance compared with blue and green lights in high turbidity water.[9–14] Therefore, an underwater wireless red-light laser transmission (UWRLLT) system is expected to provide a short-distance underwater high-speed link, similar to Wi-Fi-on-air in terms of function. In the situation of increasing popularity of oceanic exploration and oceanic leisure activities, the sense of distance experienced underwater or in the ocean is more obvious than that on the land. Whether it is for activity, construction, exploration and tracking, or research and development, underwater communication facility is in urgent need for managing site condition, making UWRLLT extremely attractive to the application of underwater communication.

UWRLLT systems are used to transmit data in water using red laser. In this study, a 10-Gbps 16-quadrature amplitude modulation (QAM)–orthogonal frequency-division multiplexing (OFDM) modulation UWRLLT system based on a high-speed multimode 680-nm vertical-cavity surface-emitting laser (VCSEL) is proposed and experimentally demonstrated. The 16-QAM-OFDM is a modulation by which the information bits are transferred into four low-speed bit-streams then modulated to perpendicular subcarriers after being encoded and inserting the synchronization and lead element. The system was employed to demonstrate a blue-light laser underwater transmission system.[15–17] The 16-QAM-OFDM has a very high-frequency effect because it can transmit nearly four times the amount of data at a low digital rate. To the best of the authors' knowledge, this study is the first attempt to adopt a 680-nm VCSEL transmitter in a 10-Gbps 16-QAM-OFDM UWRLLT system. After studying the frequency response of the system and 16-QAM-OFDM modulation parameters, a performance with a bit rate of 10 Gbps at a bit error rate (BER) of 2.9×10^{-4} is obtained from a 6-m underwater transmission using the UWRLLT system. BER is a good guarantee of the quality of communication due to its significantly lower value than the forward error correction (FEC) limit of 3.8×10^{-3}. In contrast to a high-speed underwater blue-laser wireless system,[15] the UWRLLT system has a simpler configuration, lower cost, and lower BER.

2 Experimental Setup

Figure 1 shows the configuration of the proposed 10-Gbps 16-QAM-OFDM UWRLLT system that adopts a 680-nm red-light VCSEL transmitter. The VCSEL, with wavelength range/color of 679 to 681 nm/red, is directly modulated by a 16-QAM-OFDM data stream. An 16-QAM-OFDM data signal generated offline by the MATLAB program is fed into an arbitrary waveform generator (AWG, Tektronix 7102), and pseudorandom bit sequence data streams with a length of $2^{15} - 1$ are converted into parallel binary data by a serial-to-parallel (S/P) module. After being encoded, the signal

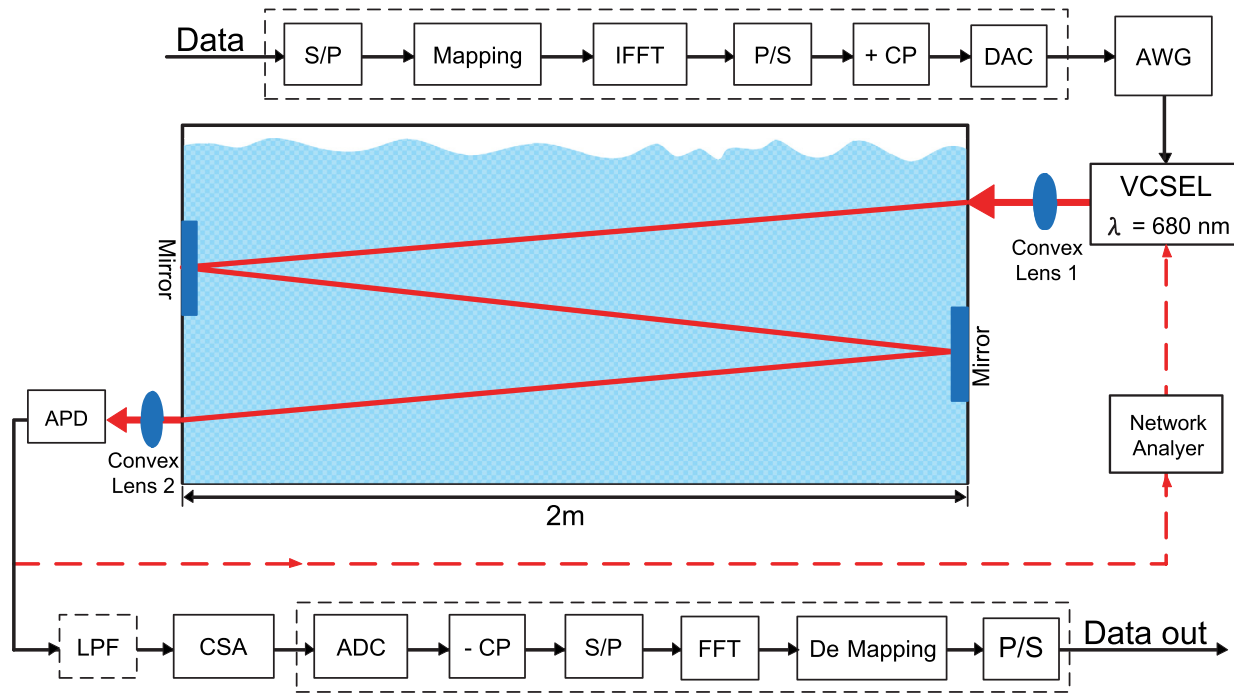*Address all correspondence to: Chung-Yi Li, E-mail: cyli@ntut.edu.tw

Fig. 1 Configuration of the proposed 10-Gbps 16-QAM-OFDM UWRLLT system with a VCSEL transmitter.

is modulated onto orthogonal subcarriers. The OFDM signals generated by an inverse fast Fourier transform (IFFT) was added with a cyclic prefix (CP) before the 16-QAM-OFDM data are converted into parallel binary data by the S/P module. The signal is fed into the AWG after being converted into analog signals using a digital-to-analog converter. The 10-Gbps 16-QAM-OFDM signal from the AWG is supplied to the 680-nm VCSEL after a bias tee (Bias-T), by which the VCSEL is directly modulated. The light sent out from the VCSEL is fed into the convex lens 1 and transmitted underwater in a water tank and then coupled into convex lens 2 at the receiving site. The function of convex lens 1 is to generate a collimated light beam, whereas convex lens 2 is to couple the collimated light beam into a point. The work range of wavelength of both two convex lens is 350 to 700 nm. The diameter of the collimated light beam is 0.6 mm with a focal length of 5.12 mm. The size of the water tank is 2 m × 1.5 m × 0.8 m, which is full of tap water with decay factor of 0.074 m^{-1} and the temperature at 23°C.[18] Several mirrors are placed on the side of both water tanks to reflect light three times for extending underwater light transmission distance over 6 m (3 × 2 m). At convex lens 2, which is the receiving side, the transmitted light signal is received by an avalanche photodetector (APD). The signal from an APD is transmitted into a communication signal analyzer (CSA, Tektronix CSA7404B), whereas the signal data output by the CSA is imported into a computer for demodulation and handled offline via MATLAB processing. After the S/P, analog to digital conversion (ADC) and being subtracted from the CP, the OFDM signals are converted using FFT. For evaluating the BER performance and the corresponding star map, the signal is demodulated by a 16-QAM before the BER value is calculated.

In addition, Fig. 1 shows the measurement setup of the frequency response of the 680-nm VCSEL transmitter in the 10-Gbps 16-QAM-OFDM UWRLLT system. An RF sweep signal (10 MHz to 40 GHz) is generated from a network analyzer and fed into the 680-nm VCSEL. The received RF sweep signal from APD detection is fed into the network analyzer. The frequency response of the 680-nm VCSEL shows the measurement result under different transmission distances for the back-to-back (BTB) and UWRLLT systems.

3 Experimental Results and Discussion

Figure 2 shows the frequency response of the 680-nm VCSEL for BTB and the frequency response of the UWRLLT system over different underwater distances. If the sudden drop at 3.8 GHz is ignored, then the 3-dB bandwidth for BTB is 4.7 GHz. However, through a 2-m underwater transmission, the 3-dB bandwidth is at 3.6 GHz before
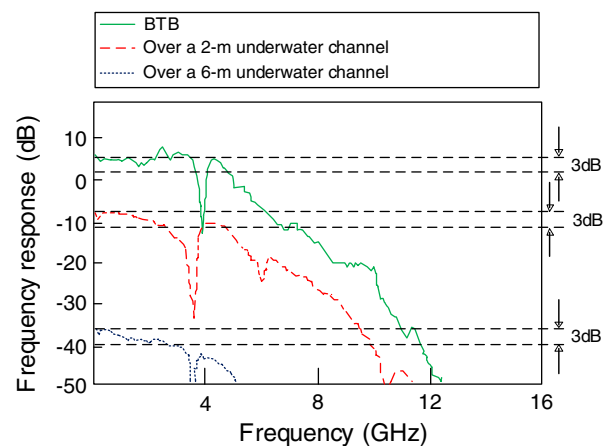

Fig. 2 Frequency responses of the 680-nm VCSEL for the BTB and UWRLLT systems over various underwater distances.

the sudden drop at 3.8 and 2.6 GHz, respectively, before the sudden drop at 3.6 GHz. Meanwhile, through a 6-m underwater transmission, the 3-dB bandwidth is at 2.7 GHz before the sudden drop at 3.6 GHz. With the use of the OFDM base 2.5-GHz bandwidth, a 10-Gbps 16-QAM-OFDM signal can be transmitted in good condition. The start frequency of the OFDM base bandwidth shall be higher than 109 MHz because a drop of nearly 1 dB occurs at ∼109 MHz. Through the 2-m underwater transmission, the BER of the 10-Gbps 16-QAM-OFDM system is at 2.7×10^{-6}, with an OFDM base bandwidth frequency of 130 MHz to 2.63 GHz ($0.13 + 2.5 = 2.63$). Using an OFDM base bandwidth of 200 MHz to 2.7 GHz ($0.2 + 2.5 = 2.7$), the BER of the 10-Gbps 16-QAM-OFDM system is 7.2×10^{-13} through the 2-m underwater transmission. Therefore, the OFDM base bandwidth from 200 MHz to 2.7 GHz is selected for the study.

Figure 3 shows the spectrum of the 10-Gbps 16-QAM-OFDM data signal through the AWG and underwater transmission. Figure 3(a) shows the spectrum of the data signal from AWG, with 28 dB between the receiving signal and nearby noise. Figure 3(b) shows the spectrum of the data signal through a 2-m underwater transmission with 18 dB between the receiving signal and nearby noise and 12 dB between them at 4 GHz. With a low-pass filter (LPF) as shown in Fig. 1, the BER is 4.9×10^{-13} through the 2-m underwater transmission, which is slightly below the BER value (7.2×10^{-13}) without employing LPF. However, the LPF was not adopted due to cost consideration. Figure 3(c) shows the spectrum of the data signal through the 6-m underwater transmission with 7 dB between the receiving signal and nearby noise. Although the signal-to-noise ratio decreases with the extension of the underwater transmission distance, the receiving signal remains easy to identify
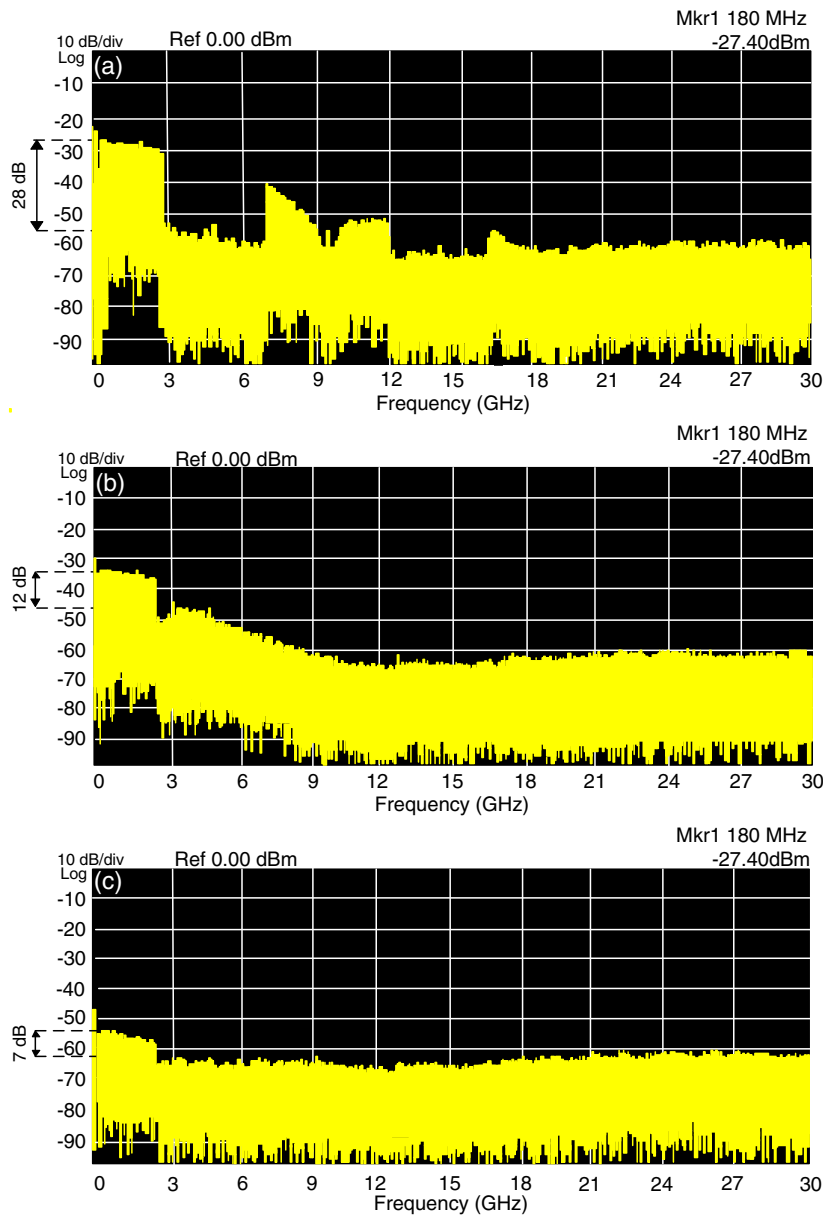

Fig. 3 Spectra of the 10-Gbps 16-QAM-OFDM data signal over varying underwater distances (a) AWG, (b) 2-m underwater transmission, and (c) 6-m underwater transmission.

through the 6-m underwater transmission. Furthermore, through an 8-m underwater transmission, the receiving signal is almost as weak as the noise and difficult to capture.

The positive transformation formula of the FTT can be expressed as follows:

$$X(k) = \text{FFT}[x(n)] = \sum_{n=0}^{N-1} x(n) W_N^{kn},$$

$$k = 0, 1, \ldots, N-1, \quad W_N = e^{-j\frac{2\pi}{N}}. \tag{1}$$

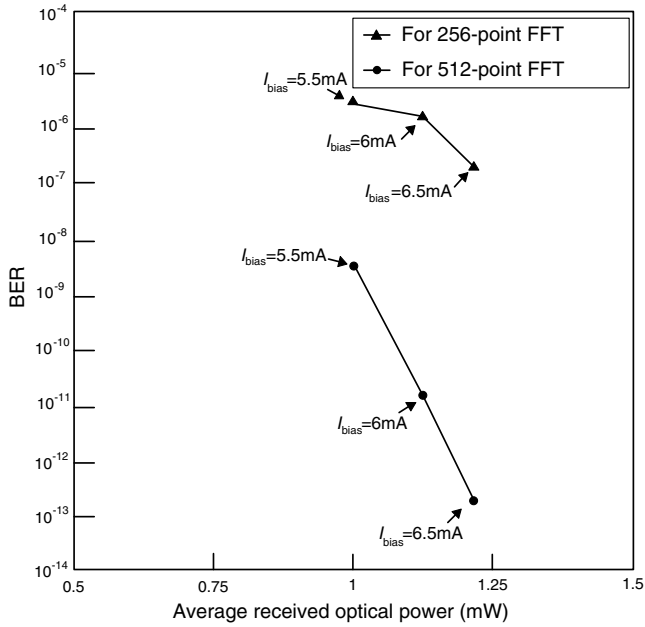The inverse transformation formula of the FTT can be expressed as follows:

Fig. 4 Measured BER curves of the 10 Gbps 16-QAM-OFDM signal through the 2-m underwater transmission for the 512- and 256-point FFT.

$$x(n) = \text{IFFT}[X(k)] = \frac{1}{N} \sum_{n=0}^{N-1} X(k) W_N^{kn},$$

$$k = 0, 1, \ldots, N-1, \tag{2}$$

where N is associated with the spectral resolution that affects BER. Figure 4 shows the measured BER curves of the 10-Gbps 16-QAM-OFDM signal through the 2-m underwater transmission for the 512- and 256-point FFT. The BER of the 512-point FFT is significantly lower than that of the 256-point FFT. Although the spectral resolution can be improved further by a 1024-point FFT, computational complexity significantly increases, which causes further device complexity and cost. Thus, the 512-point FFT is selected.

Figure 5(a) shows the optical output power of the 680-nm VCSEL at different biases. A maximum power of 5.76 mW is obtained when the bias current is increased to 8.5 mA. The lowest BER is measured at a bias current of 6.5 mA. The received power (P) after underwater transmission can be expressed as follows:

$$P = P_o e^{-c(\lambda)d}, \tag{3}$$

where P_o is the power of transmitted light, d is the light transmission distance, and $C(\lambda)$ is the attenuation coefficient. When the bias current is 6.5 mA, the measured P at the 2-, 4-, and 6-m underwater transmission are 1.2, 0.4, and 0.15 mW, respectively. Meanwhile, the P_o at 6.5 mA is 4.34 mW. The $e^{-c(\lambda)d}$ of the 2-, 4-, and 6-m underwater transmission is calculated using Eq. (3) as 1.2/4.34, 0.4/4.34, and 0.15/4.34, respectively. The P of other bias currents can be given by Eq. (3) and $C(\lambda)$ in Fig. 5(b). The experimental result can be seen clearly from Fig. 5(b) that as the transmission distance d becomes longer, the receiving power P becomes smaller. In addition, by introducing the above experimental result into Eq. (3), we obtained the result of $C(\lambda)$ approaching to a constant value. As the light source of the system is of single wavelength ($\lambda = 680$ nm), and while $C(\lambda)$ happens to have a direct relationship with the wavelength used, we obtained the result and trend of $C(\lambda)$ approaching to a constant value through the comparison between the
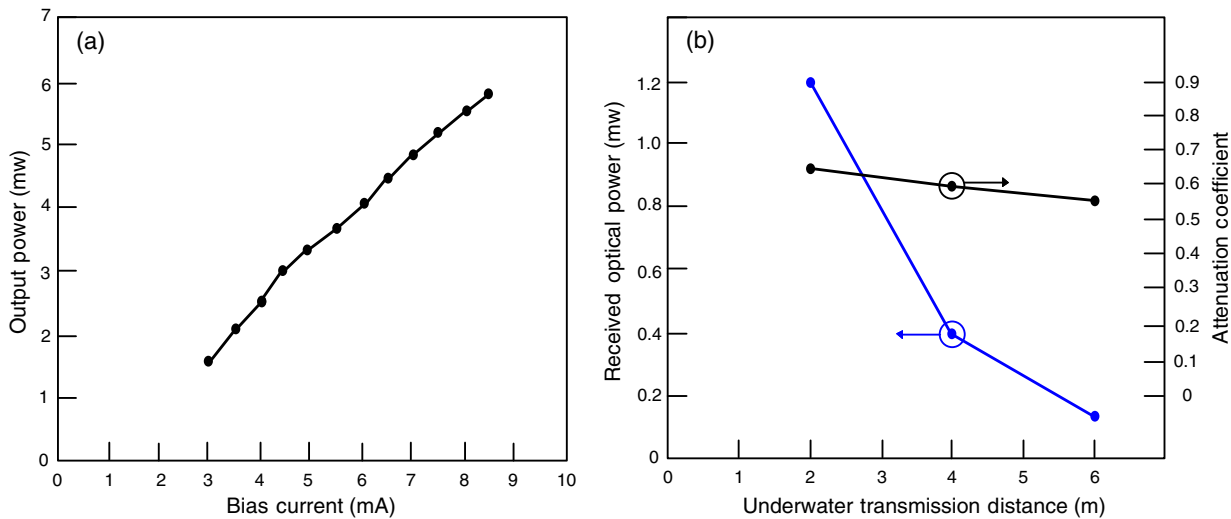

Fig. 5 (a) Optical output power of the 680-nm VCSEL at different biases and (b) the received light power and attenuation coefficient under different underwater transmission distances.
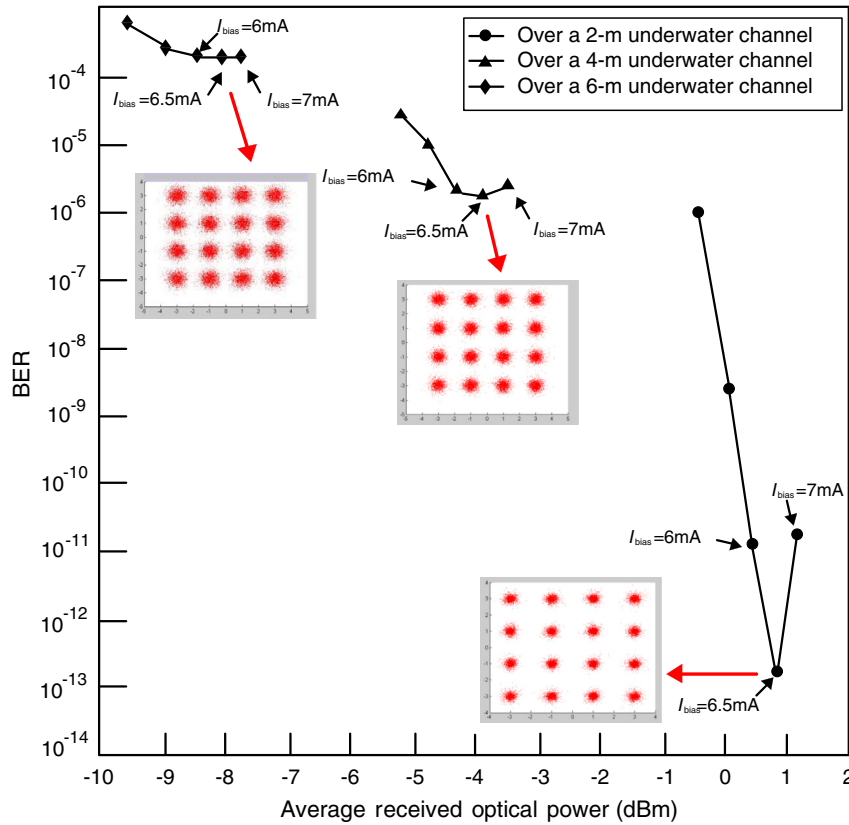
Fig. 6 Measured BER curves of the 10-Gbps 16-QAM-OFDM data signal versus average received optical power over various underwater distances.

experimental result and the theory in Eq. (3), which verified the rightness of the trend of experimental result and the theory in Eq. (3).

Figure 6 shows the measured BER curves of the 10-Gbps 16-QAM-OFDM data signal versus average received optical power over varying underwater distances. Corresponding constellation maps are included among the curves. The measured BER of the 2-, 4-, and 6-m underwater transmission is 7.2×10^{-13}, 3.2×10^{-6}, and 2.9×10^{-4}, respectively. Even for a BER of 2.9×10^{-4}, it is significantly lower than the FEC limit of 3.8×10^{-3}. Good BER performance and constellation maps are obtained to demonstrate the feasibility of

establishing a 6-m/10-Gbps UWRLLT system based on a 680-nm VCSEL.

An even lower BER can be derived by employing LNA and equalisers before the signal is transmitted into CSA[4,15] or using a MATLAB process of equalization before demapping.[14] Considering a lower system cost and a significantly low BER of 2.9×10^{-4} compared with the FEC limit, the LNA and equalizer are not adopted in this study. In contrast to the 10-Gbps blue light UWLT system,[15] the UWRLLT system has a simpler configuration, lower cost, and lower BER (as listed in Table 1). In the 10-Gbps blue light UWLT system, a 405-nm blue laser diode (LD),

Table 1 The comparison between the proposed UWRLLT system and previous studies.

Reference	Emission end	Receiving end	Data format/transmission rate (Gbps)	Distance/BER
Ref. 15	Two ~405-nm blue light LD and one PD were used for light injection and optoelectronic feedback techniques.	A PD is used along with LNA and equalizer.	16-QAM-OFDM/10 Gbps	5 m/4.6 × 10⁻³ (without LNA and equalizer) 5 m/1 × 10⁻⁷ (with LNA and equalizer).
Proposed	Single 680-nm VCSEL	Single APD	16-QAM-OFDM/10 Gbps	6 m/2.9 × 10⁻⁴
Comparison	The system in Ref. 15 has one more LD and PD, which is more complex and of higher cost.	With additional LNA and equalizer, the system in Ref. 15 is more complex and of higher cost.	Same	Under the same condition without LNA and equalizer, the configuration of our system performs better than that in Ref. 15 in respect of distance and BER.

404.97-nm LD, an optical isolator, 1×2 optical splitter, polarization controller, and two PDs are used to improve the transmission data rate. According to the measured BER curves, the BER over the 6-m underwater link is only 10^{-3} without the LNA and equalizer.

4 Conclusion

A high-speed 16-QAM-OFDM modulation UWRLLT system is proposed and experimentally demonstrated. With proper selection of bandwidth and modulation parameters, the high-speed multimode 680-nm VCSEL can suffice the need for the transmission of 16-QAM-OFDM signals. Our study is the first one that employs a red-light transmitter in the 10 Gbps 16-QAM-OFDM communication. The performance of the 6-m underwater transmission for the proposed high-speed 10-Gbps 16-QAM-OFDM communication is evaluated using BER and constellation maps. This proposed high-speed 16-QAM-OFDM modulation UWRLLT communication system is an eminent alternative for short-reach underwater wireless communication at high transmission rates.

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Xu-Hong Huang received her MS degree from the College of Physics and Information Engineering, Fuzhou University, China, in 2003. She joined Fujian Hitachi TV as an engineer in 1990 and was promoted to senior engineer in 2000. She joined the School of Information Science and Engineering, Fujian University of Technology as an associate professor in 2003. Her research interests include optical wireless transmission systems, and underwater wireless optical communication systems. She has authored or coauthored more than 20 papers in national journals and more than 8 papers in international conferences.

Chung-Yi Li received his MS and PhD degrees from the Department of Electro-Optical Engineering, National Taipei University of Technology, Taiwan, in 2008 and 2012, respectively. From 2013 to 2014, he was an engineer with the Innovation and Product Development Department, FOCI Fiber Optic Communications, Inc., Hsinchu, Taiwan. In 2014, he joined the Department of Electro-Optical Engineering, National Taipei University of Technology as a research assistant professor. His research interests include visible/invisible light communication, underwater wireless optical communication systems, PAM4 transmission systems, and fiber optical CATV transport systems.

Hai-Han Lu received his MS and PhD degrees from the Institute of Electro-Optical Engineering, National Central University, Taiwan, in 1991 and 2000, respectively. After joining the Department of Electro-Optical Engineering, NTUT as an associate professor in 2001, he was promoted to professor, distinguished professor, and life distinguished professor in 2003, 2006, and 2017, respectively. His research interests include underwater wireless laser-transmission systems, visible/invisible laser light communications, PAM4/PAM8 transmission systems, and fibre–wireless transmission systems. He has authored or coauthored more than 200 papers in SCI cited international journals and more than 120 papers in international conferences.

Chung-Wei Su received his BS degree from Tamkang University, New Taipei, Taiwan, in 2017. Now, he is currently working towards an MS degree at the Institute of Electro-Optical Engineering, National Taipei University of Technology (NTUT), Taiwan.

You-Ruei Wu received his BS degree from Fu Jen University, Taipei, Taiwan, in 2017. Now, he is currently working towards an MS degree at the Institute of Electro-Optical Engineering, National Taipei University of Technology (NTUT), Taiwan.

Zhen-Han Wang received his BS degree from National Formosa University, Yunlin, Taiwan, in 2017. Now, he is currently working towards an MS degree at the Institute of Electro-Optical Engineering, National Taipei University of Technology (NTUT), Taiwan.

Yong-Nian Chen received his BS degree from Mingshin University, Hsinchu, Taiwan, in 2017. Now, he is currently working towards an MS degree at the Institute of Electro-Optical Engineering, National Taipei University of Technology (NTUT), Taiwan.