IEEE Photonics Journal
An IEEE Photonics Society Publication

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Volume 10, Number 3, June 2018

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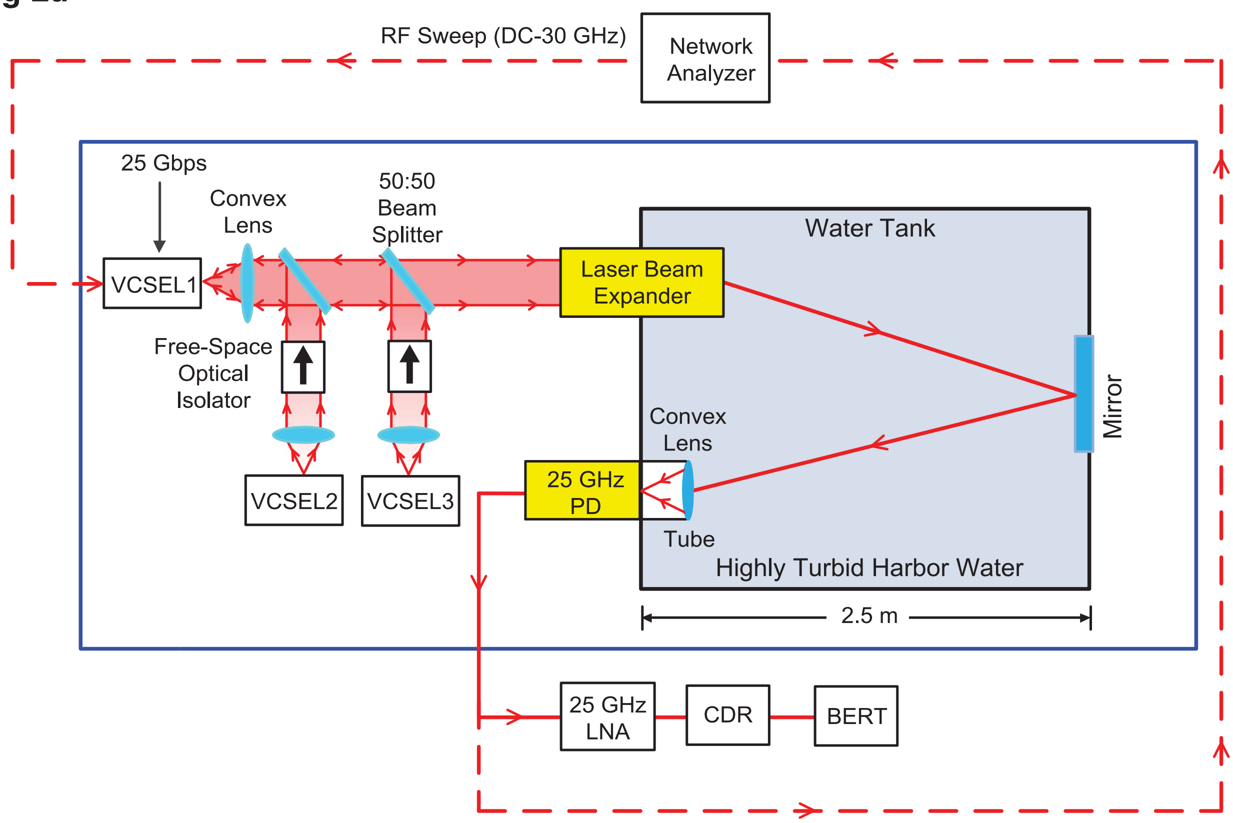

DOI: 10.1109/JPHOT.2018.2842762
1943-0655

IEEE photonics SOCIETY
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A 5 m/25 Gbps Underwater Wireless Optical Communication System

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DOI:10.1109/JPHOT.2018.2842762

Manuscript received April 19, 2018; revised May 21, 2018; accepted May 29, 2018. Date of publication June 1, 2018; date of current version June 18, 2018. Corresponding author: H.-H. Lu (e-mail: hhlu@ntut.edu.tw).

Abstract: A 25-Gbps underwater wireless optical communication (UWOC) system with a two-stage injection-locked 680-nm red-light vertical-cavity surface-emitting laser (VCSEL) transmitter to enhance the frequency response and a laser beam expander to expand the collimated beam diameter over a 5-m highly turbid harbor water link is proposed and practically demonstrated. In highly turbid harbor water link, the overall attenuation coefficient at 680 nm is smaller than that at 520 and 450 nm, thereby a 680-nm red-light VCSEL transmitter is adopted in this proposed 5 m/25 Gbps UWOC system rather than a 520-nm green-light laser diode (LD) transmitter or a 450-nm blue-light LD transmitter. A satisfactory bit error rate performance (3×10^{-9}) and a clear eye diagram are acquired in real time. This proposed UWOC system with a two-stage injection-locked 680-nm VCSEL transmitter and a laser beam expander brings important improvements in the scenario characterized by high turbidity.

Index Terms: Laser beam expander, two-stage injection-locked, underwater wireless optical communication, vertical-cavity surface-emitting laser.

1. Introduction

Underwater wireless optical communication (UWOC) has elicited significant interest over the past few years as a potential provider of high-speed underwater links. Some recent works have shown that high-speed UWOC systems can be established over limited underwater links [1], [2]. Many applications of UWOC systems have been proposed for environmental monitoring, offshore exploration, disaster precaution, and underwater oil pipe investigation. To satisfy the requirements of different applications, a high-speed UWOC system with limited underwater link is needed. The transmissions of several Gbps with 16-quadrature amplitude modulation (QAM)-orthogonal frequency-division multiplexing (OFDM) [3], four-level pulse amplitude modulation (PAM4) [4], or non-return-to-zero on-off-keying (NRZ-OOK) [5]–[7] data format have been implemented in high-speed UWOC systems. However, the transmissions of several tens of Gbps with NRZ-OOK data format has not been implemented in high-speed UWOC systems. To compare with NRZ-OOK, 16-QAM-OFDM is more sensitive to nonlinear distortions, by which causing intermodulation between the subcarriers and leading to performance degradation in the quality of underwater communication. As for the PAM4, although PAM4 enables twice the transmission capacity in comparison with NRZ-OOK; nevertheless, PAM4 signal is more susceptible to noise than NRZ-OOK signal. Moreover, UWOC systems with 16-QAM-OFDM or PAM4 signal must be processed offline for the analysis of bit error rate (BER) performance. However, this process increases the complexity of UWOC systems. For a real implementation of UWOC system, establishing a high-speed underwater link with low complexity and satisfactory performance is significant. An UWOC system with NRZ-OOK signal format is a feasible way by which transmission performances in view of BER and eye diagram are analysed in real-time. It is attractive because it prevents the offline processing via MATLAB.

Two-stage injection-locked technique has been employed in a high-speed light-based WiFi (LiFi) transmission system to amend the performances of systems [8]. Nevertheless, it has not been adopted as a system performance improvement technique in a high-speed UWOC system, which is similar to LiFi transmission system because both use optical wavelengths to transmit data signals between dedicated point-to-point links. Two-stage injection-locked technique is thereby expected to provide good overall transmission performances in a high-speed UWOC system. In this demonstration, a 25-Gbps NRZ-OOK UWOC system with a two-stage injection-locked 680-nm vertical-cavity surface-emitting laser (VCSEL) transmitter to enhance the frequency response and a laser beam expander to expand the collimated beam diameter [9] over a 5-m highly turbid harbor water link is proposed. In highly turbid harbor water link, the overall attenuation coefficient at 680 nm (red-light) is smaller than that at 520 nm (green-light) or 450 nm (blue-light) [7]. Thus, a 680-nm VCSEL transmitter employing a two-stage injection-locked technique is adopted in a 5 m/25 Gbps UWOC system. Additionally, scattering is the dominant factor in highly turbid harbor water. Given a laser beam expander for the expansion of the collimated beam diameter, the transmission performance of UWOC systems with highly turbid harbor water link is improved because of the higher amounts of light received by optical receiver (more forward-scattered light received by optical receiver). We successfully show that a 25-Gbps data stream (NRZ-OOK data format) can be delivered to a maximum of 5-m highly turbid harbor water link. To our understanding, it is the first link to employ a two-stage injection-locked 680-nm VCSEL transmitter and a laser beam expander in a high-speed 25-Gbps NRZ-OOK UWOC system. This is not the first NRZ-OOK UWOC system demonstrated. However, this is the world fastest NRZ-OOK UWOC system ever at the best of the author's knowledge. Satisfactory BER performance and clear eye diagram are acquired in real-time over a 5-m highly turbid harbor water link. Such an UWOC system with two-stage injection-locked 680-nm VCSEL transmitter for enhancing frequency response and laser beam expander for expanding collimated beam diameter is better than previous UWOC systems due to its workability for high-speed underwater links.

2. Experimental Setup

Fig. 1 illustrates the structure of the proposed 5 m/25 Gbps UWOC system that uses a two-stage injection-locked 680-nm red-light VCSEL transmitter and a laser beam expander for expanding collimated beam diameter. The VCSEL1 (Vixar 680C-0000-G002), with wavelength/3-dB bandwidth/power/package of 681.74–682.12 nm/5.3 GHz/3–4.6 dBm/TO-46, is directly modulated by a pseudorandom binary sequence data stream at 25 Gbps with a length of $2^{15}-1$. For the part of two-stage injection locking, the VCSEL2 (Vixar 680C-0000-G002) is used as the first-stage injection light source with an injection power level of 3$\sim$4.6 dBm, and the VCSEL3 (Vixar 680C-0000-G002) is used as the second-stage injection light source with an injection power level of 3$\sim$6.3 dBm. All VCSELs (VCSEL1, VCSEL2 and VCSEL3) have the same optical characteristics. The parallel optical beam sent out from the two-stage injection-locked VCSEL is fed into a laser beam expander for expanding collimated beam diameter. After that, the laser beam is delivered in the highly turbid harbor water, coupled into a convex lens, and concentrated on a 25-GHz photodiode (PD). The water tank (2.5 m $\times$ 0.6 m $\times$ 0.5 m) is loaded with highly turbid harbor water. The high turbidity of the underwater condition is produced with suspensions of $Al(OH)_3$ and $Mg(OH)_2$, which are obtained by adding a commercial antacid preparation (Maalox). This approach is commonly used in laboratory experiments to provide scattering. The underwater link is enhanced to 5 m (2.5 m $\times$ 2) with the

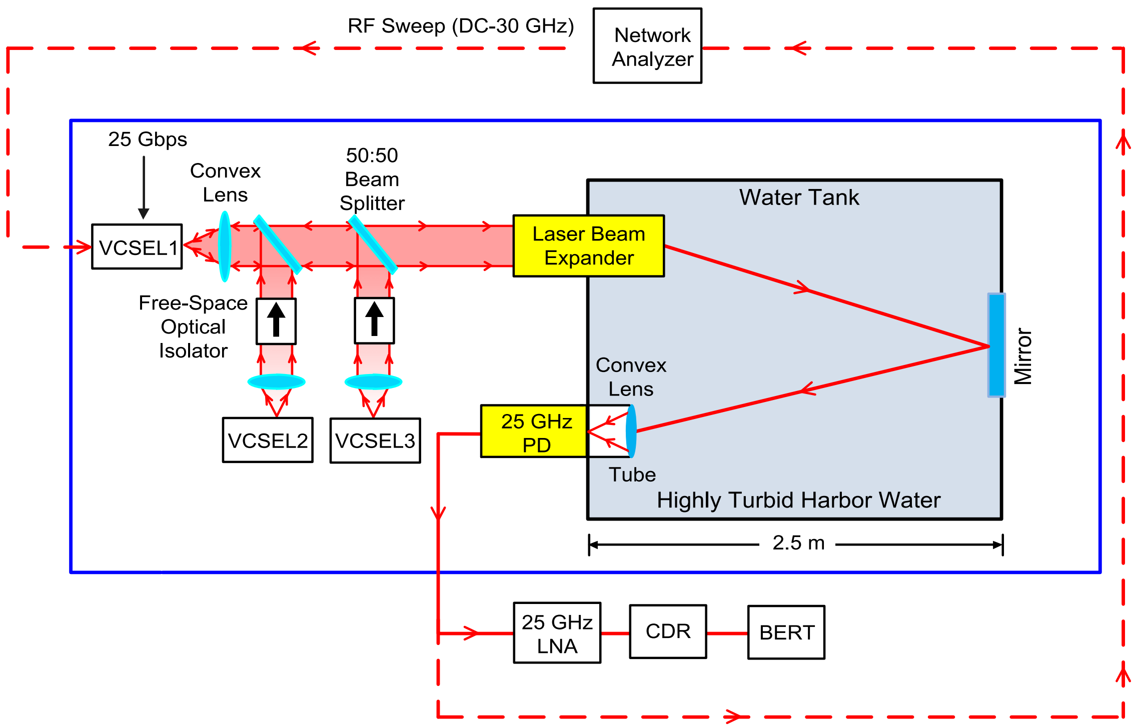

Fig. 1. The structure of the proposed 5 m/25 Gbps UWOC system with a two-stage injection-locked 680-nm red-light VCSEL transmitter and a laser beam expander for expanding collimated beam diameter.

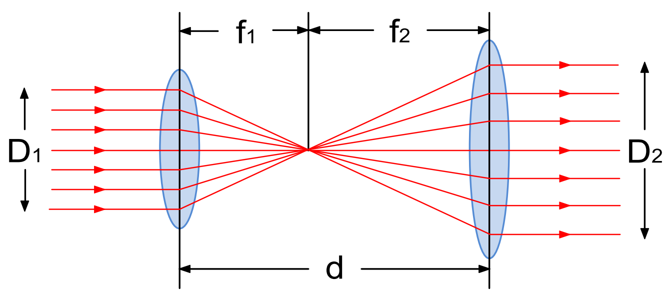

Fig. 2. The laser beam expander for the expansion of collimated beam diameter.

assistance of a reflective mirror on the right side of the water tank. After PD detection, the received data stream is boosted by a 25-GHz low noise amplifier (LNA), retrieved by a 25-Gbps clock/data recovery (CDR), and sent to a BER tester (BERT) for BER performance analysis. Additionally, the measurement of the frequency responses of the 680-nm VCSEL transmitter-based UWOC systems is also shown in Fig. 1. The frequency responses of the 680-nm VCSEL transmitter-based UWOC systems are measured under different conditions, namely, free-running, one-stage injection locking, and two-stage injection locking.

The laser beam expander for the expansion of collimated beam diameter is presented in Fig. 2. The laser beam expander adopted in a 5 m/25 Gbps UWOC system is made up of two convex lenses with dissimilar focal lengths of f_1 and f_2 ($f_1 < f_2$). The summation of the focal lengths is equivalent to the separation distance of two convex lenses ($f_1 + f_2 = d$). A collimated beam with a diameter of 4.4 mm is sent to the laser beam expander. Two convex lenses with focal lengths of 25.4 mm (f_1) and 50 mm (f_2) are adopted. The laser beam expander converts a 4.4-mm small collimated beam diameter (D_1) into an 8.7-mm large one (D_2). Furthermore, we change two convex lenses with dissimilar focal lengths of 50 mm (f_1) and 25.4 mm (f_2) for the reduction of collimated beam diameter. Under this scenario, the laser beam reducer transforms a large collimated beam diameter (D_1) of 4.4 mm into a small one (D_2) of 2.2 mm.

3. Experimental Results and Discussions

In underwater channel, the light attenuation effect can be obtained as:

$$P_d = P_0 e^{-c(\lambda)d} \quad (1)$$

where P_0 is the power of laser diode (LD) transmitter, P_d is the power of light over a *d*-distance underwater link, $c(\lambda)$ is coefficient of water associated with attenuation. The attenuation coefficient $c(\lambda)$ is given by:

$$c(\lambda) = a(\lambda) + s(\lambda) \quad (2)$$

where $a(\lambda)$ and $s(\lambda)$ are coefficients of water associated with absorption and scattering. $a(\lambda)$ and $s(\lambda)$ can be expressed as [10], [11]:

$$a(\lambda) = a_w(\lambda) + 0.06a_c(\lambda)C^{0.65} + 0.2e^{-0.014(\lambda-440)} \quad (3)$$

$$s(\lambda) = 0.3\frac{550}{\lambda}C^{0.62} \quad (4)$$

where $a_w(\lambda)$ is the water absorption, $a_c(\lambda)$ is the chlorophyll absorption, and C is the chlorophyll concentration. In highly turbid harbor water link, the value of chlorophyll concentration (C) is 19 $(\mathrm{mg} \cdot \mathrm{m}^{-3})$. Given that the parameters of highly turbid harbor water of λ, C, $a_w(\lambda)$ and $a_c(\lambda)$ are known, the values of $a(\lambda)$, $s(\lambda)$ and $c(\lambda)$ can be obtained based on Eqs. (2)–(4), as listed in Table 1 [12]. Clearly, the scattering coefficient $s(\lambda)$ and attenuation coefficient $c(\lambda)$ at 680 nm are smaller than those at 520 nm and 450 nm. With low scattering and attenuation coefficients, the transmission performances of UWOC systems in highly turbid harbor water link can be improved due to higher amounts of light received by PD (lower amounts of light attenuated by highly turbid harbour water). This finding shows that red-light outperforms blue-light and green-light in highly turbid water channel. The scattering and attenuation are lower at 680 nm for such specific scenario (highly turbid harbor water). However, it is not the common case in clear/costal ocean water. It should be noted that blue-light is typically better for clear ocean water, and green-light is typically better for coastal ocean water. In clear/costal ocean water, red-light suffers from larger absorption whereas its advantage on smaller scattering is not significant. In clear/costal ocean water link, the blue-light/green-light outperforms the red one.

The frequency responses of 680-nm VCSEL-based UWOC systems under different conditions are shown in Fig. 3. For the condition of free-running, the 3-dB bandwidth is 5.3 GHz. As expected, for the condition of two-stage injection locking, the 3-dB bandwidth is enhanced to 26.1 GHz. This 3-dB bandwidth enhancement (5.3 GHz→26.1 GHz) is due to the effect of two-stage injection locking. The laser resonance frequency f_0 can be stated as:

$$f_0^2 = \frac{g_0 P}{4\pi^2 \tau_p} \quad (5)$$

where g_0 is the gain coefficient, P is the photon density, and τ_p is the photon lifetime. Two-stage injection locking increases the photon density significantly, which leads to a great improvement of laser resonance frequency. Thereby, the frequency responses of 680-nm VCSEL-based UWOC systems is improved significantly [8]. Accordingly, a two-stage injection-locked 680 nm VCSEL transmitter is developed for a high-speed 25-Gbps UWOC system. 680 nm edge emitting laser, such as distributed feedback laser or Fabry-Perot laser, with two-stage injection locking could be adopted in this UWOC systems. As far as we know, nevertheless, the maximum 3-dB bandwidth of 680 nm laser is 5.3 GHz (VCSEL, Vixar 680C-0000-X002). In order to have a great 3-dB bandwidth enhancement after two-stage injection locking, VCSEL with a 3-dB bandwidth of 5.3 GHz is adopted

Table 1
Parameters of Highly Turbid Harbor Water at 450 nm (Blue-Light), 520 nm (Green-Light), and 680 nm (Red-Light)

λ (nm)	C (mg·m^{-3})	$a_\omega(\lambda)$ (m^{-1})	$a_c(\lambda)$ (m^{-1})	$a(\lambda)$ (m^{-1})	$s(\lambda)$ (m^{-1})	$c(\lambda)$ (m^{-1})
450	19	0.015	0.944	0.5729	2.2756	2.8485
520	19	0.048	0.528	0.3280	1.9693	2.2973
680	19	0.450	0.502	0.6611	1.5059	2.1670

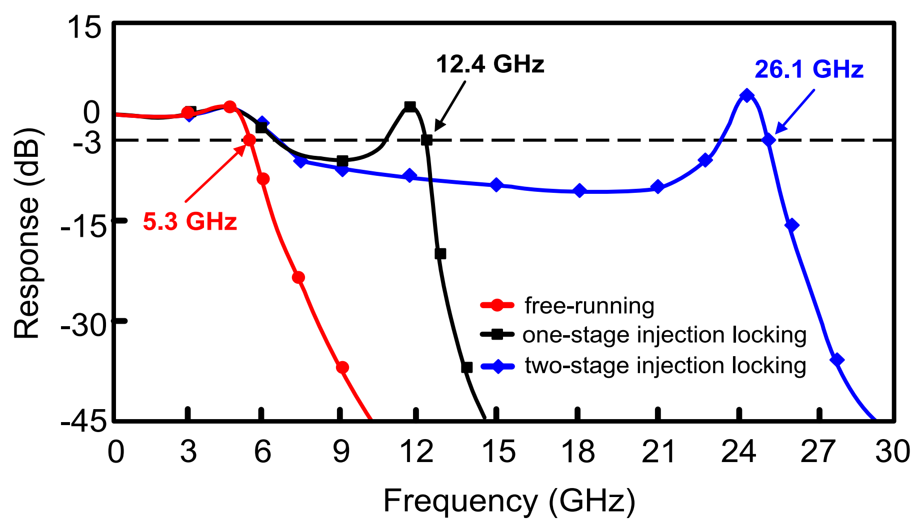

Fig. 3. The frequency responses of the 680-nm VCSEL-based UWOC systems under different conditions.

to realize the high-speed UWOC systems, instead of edge emitting laser. In comparison with other previous studies (as listed in Table 2) [1]–[7], complicated offline process by MATLAB and costly arbitrary waveform generator/PAM4 generator [1]–[4] are not required in this proposed 25-Gbps UWOC system. Former researches demonstrated 2.7 Gbps [5], 1.5 Gbps [6], and 2.3 Gbps [7] UWOC systems using NRZ-OOK signal format. However, the transmission rates of 2.7 Gbps, 1.5 Gbps, and 2.3 Gbps are significantly less than 25 Gbps adopted in this proposed NRZ-OOK UWOC system. This demonstrates a significant improvement with simpler and higher transmission rate advantages than those of 16-QAM-OFDM/32-QAM-OFDM/PAM4/NRZ-OOK UWOC systems. Meanwhile, although the proposed NRZ-OOK UWOC systems have low energy efficiency and spectral efficiency, they are simple and exhibit high transmission rate characteristics. Thus, NRZ-OOK modulation is still worth adopting in the proposed 25-Gbps UWOC systems. Developing a configuration with simple characteristics and satisfactory performances are important to guarantee a real implementation. As a result, our proposed system is suitably applicable to high-speed UWOC applications.

The BER performances of the 25-Gbps UWOC systems with a two-stage injection-locked 680-nm VCSEL transmitter over a 5-m highly turbid harbor water link are shown in Fig. 4. In highly turbid harbor water link, obviously, BER performance improves with the increase of collimated beam diameter. Without a laser beam reducer/expander (with a diameter of 4.4 mm), the BER value is 5×10^{-8}. With a laser beam reducer for reducing collimated beam diameter (with a diameter of 2.2 mm), the BER value deteriorates to 10^{-6}. Using a laser beam reducer to reduce the collimated

Table 2
Comparison of the Proposed 25-Gbps UWOC System With Other Previous Studies

Reference	λ (nm)	Bandwidth (GHz)	Data Format	Underwater Link (m)	Transmission Rate (Gbps)
Ref [1]	450	1.5	16-QAM-OFDM	1.7	12.4
Ref [2]	520	1.1	32-QAM-OFDM	26	5.5
Ref [3]	405	5.4	16-QAM-OFDM	8	9.6
Ref [4]	488	8.2	PAM4	10	16
Ref [5]	520	1.4	NRZ-OOK	34.5	2.7
Ref [6]	450	1.0	NRZ-OOK	20	1.5
Ref [7]	525	1.2	NRZ-OOK	7	2.3
Proposed	680	26.1	NRZ-OOK	5	25

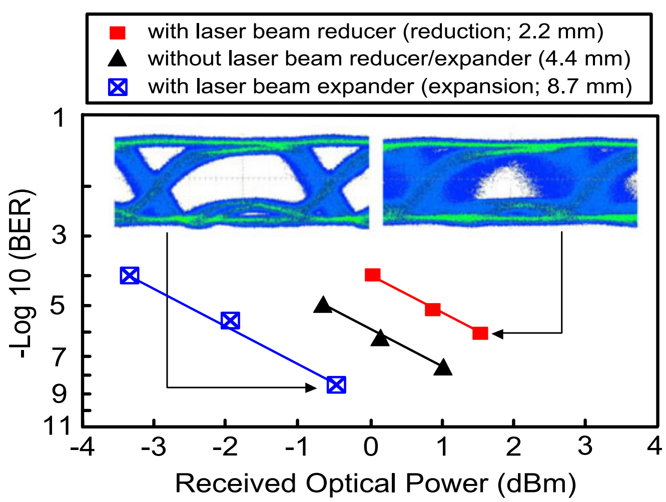

Fig. 4. The BER performances of the 25-Gbps UWOC systems with a two-stage injection-locked 680-nm VCSEL transmitter over a 5-m highly turbid harbor water link.

beam diameter will increase the beam divergence due to the conservation of the product of the beam diameter and beam divergence. A smaller collimated beam diameter causes larger beam divergence (larger scattering angle), leads to higher inter-symbol interference (ISI) and less forward-scattered light received by PD, and results in worse BER performance. With a laser beam expander for the expansion of collimated beam diameter (with a diameter of 8.7 mm), the BER value improves to 3×10^{-9}. Using a laser beam expander to expand the collimated beam diameter will reduce the beam divergence due to the conservation of the product of the beam diameter and beam divergence. A larger collimated beam diameter causes smaller beam divergence (smaller scattering angle),

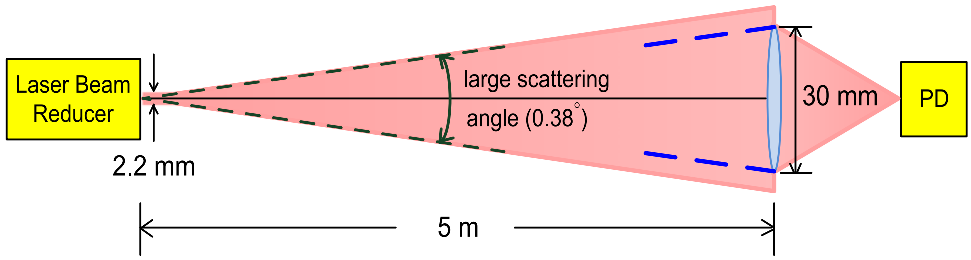

Fig. 5. For the scenario of large scattering angle of 0.38° (> 0.34°), the PD receives less forward-scattered light.

leads to lower ISI and more forward-scattered light received by PD, and results in better BER performance. In highly turbid harbor water link, since the proportion of absorbed signal is low, a larger beam diameter that accompanies higher absorption does not cause larger optical-to-signal ratio (OSNR) decrease, so other benefits of wide beam width are realized. The collimated beam diameter by which 10^{-9} BER operation can be obtained is around 8.7 mm. With a diameter of 2.2 mm, the received optical power at the receiver side is about 1.7 dBm to compensate the OSNR decrement. However, the compensation effect is limited such that only 10^{-6} BER operation is obtained. At a BER operation of 10^{-6}, a power penalty of around 3.5 dB exists between the scenario with a diameter of 8.7 mm and the scenario with a diameter of 2.2 mm. Such a power penalty of 3.5 dB results from higher ISI and less forward-scattered light received by PD due to larger beam divergence (larger scattering angle). Moreover, at the same received optical power, the optical power of the two-stage injection-locked VCSEL transmitter for the scenario with a diameter of 2.2 mm is higher than that of the scenario with a diameter of 8.7 mm (by adjusting the output power of VCSEL1 as well as the injection powers of VCSEL2 and VCSEL3), thereby leading to lower OSNR and higher BER. The eye diagrams of the 25-Gbps data stream (NRZ-OOK format) with a laser beam reducer/expander for reducing/expanding collimated beam diameter are also shown in Fig. 4. For the scenario of reducing collimated beam diameter (with a diameter of 2.2 mm), excessive amplitude and phase fluctuations are observed. However, for the scenario of expanding collimated beam diameter (with a diameter of 8.7 mm), a clear eye diagram exists.

Given that the underwater link is 5 m and the convex lens at the receiver side has a diameter of 30 mm, the maximum (acceptable) scattering angle is:

$$\sin^{-1}\left(\frac{1.5\,\text{cm}}{500\,\text{cm}}\right) \times 2 = 0.17^\circ \times 2 = 0.34^\circ \tag{6}$$

With a laser beam reducer for reducing collimated beam diameter into 2.2 mm, a large scattering angle of 0.38° (> 0.34°) happens (as shown in Fig. 5). The diameter can be calculated as:

$$500 \times \sin 0.19^\circ \times 2 = 3.32(\text{cm}) = 33.2(\text{mm}) > 30(\text{mm}) \tag{7}$$

Since that the diameter of the laser beam (33.2 mm) is larger than that of the convex lens (30 mm), yet the PD receives less forward-scattered light, thereby leading to a higher BER. Whereas with a laser beam expander for expanding collimated beam diameter into 8.7 mm, a small scattering angle of 0.3° (<0.34°) occurs (as shown in Fig. 6). The diameter can be obtained as:

$$500 \times \sin 0.15^\circ \times 2 = 2.62(\text{cm}) = 26.2(\text{mm}) < 30(\text{mm}) \tag{8}$$

Since that the diameter of the laser beam (26.2 mm) is smaller than that of the convex lens (30 mm), yet the PD receives more forward-scattered light, thereby leading to a lower BER.

The BER curves of the 25-Gbps UWOC system with a two-stage injection-locked 680-nm VCSEL transmitter and a laser beam expander for the expansion of collimated beam diameter (with a

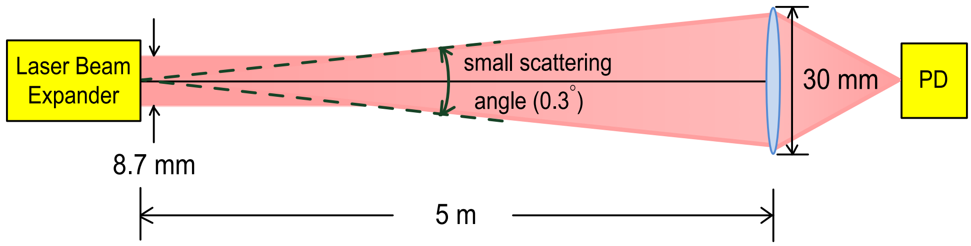

Fig. 6. For the scenario of small scattering angle of 0.3° (<0.34°), the PD receives more forward-scattered light.

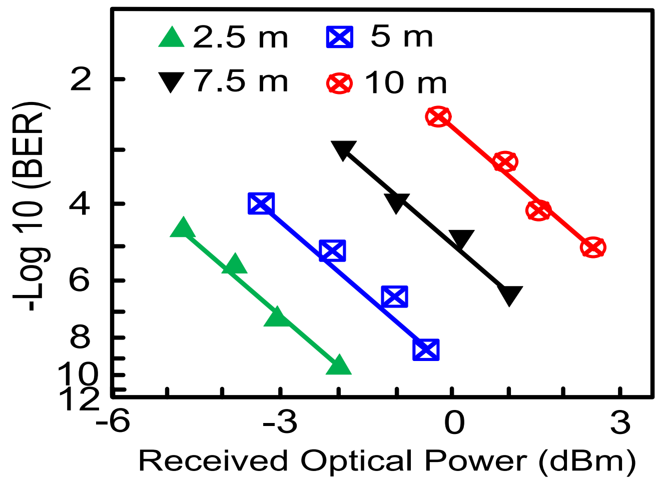

Fig. 7. The BER curves of the 25-Gbps UWOC system with a two-stage injection-locked 680-nm VCSEL transmitter and a laser beam expander for expanding collimated beam diameter (with a diameter of 8.7 mm) over a 2.5-m/5-m/7.5-m/10-m highly turbid harbor water link.

diameter of 8.7 mm) over a 2.5-m/5-m/7.5-m/10-m highly turbid harbour water link are displayed in Fig. 7. Clearly, as the underwater link increases, the BER increases as well. Over a 2.5-m highly turbid harbor water link, the BER reaches 5×10^{-10}. Over a 5-m highly turbid harbor water link, the BER is 3×10^{-9}. Over a 7.5-m highly turbid harbor water link, the BER declines to 4×10^{-7}. Over a 10-m highly turbid harbor water link, however, the BER degrades to 10^{-5}. This BER performance degradation results from the OSNR decrement because of the transmission over a 10-m highly turbid harbour water link, and optical beam misalignment between the convex lens and the active area of PD at the receiver side. A longer highly turbid harbor water link leads to higher scattering (higher attenuation), by which causing lower OSNR and higher BER. Furthermore, optical beam alignment between the convex lens and the active area of PD at the receiving site is decisive for the transmission performances of high-speed UWOC systems [13], [14]. A longer highly turbid harbor water link causes optical beam misalignment due to a small active area of PD that requires good pointing and alignment techniques between the optical transmitter and the optical receiver. As the optical beam misalignment increases the BER increases as well. The maximum underwater link by which 10^{-9} BER operation can be obtained is about 5 m. Over a 10-m highly turbid harbor water link, the received optical power at the receiver side is about 2.6 dBm to compensate the OSNR decrement. Nevertheless, it can be seen that the compensation effect is limited such that only 10^{-5} BER operation is acquired. At a BER operation of 10^{-5}, a large power penalty of around 7 dB exists between the scenario over a 2.5-m highly turbid harbor water link and the scenario over a 10-m highly turbid harbor water link. Such a large power penalty of 7 dB results from OSNR decrement and optical beam misalignment due to more transmission over a 7.5-m highly turbid harbor water link. Moreover, at the same received optical power, the optical power of the two-stage injection-locked VCSEL transmitter for the scenario over a 10-m highly turbid harbor water link is higher than that of the scenario over a 2.5-m highly turbid harbor water link (by adjusting the output power of VCSEL1 as well as the injection powers of VCSEL2 and VCSEL3), thereby resulting in lower OSNR and higher BER.

4. Conclusion

For the first time, a high-speed 25-Gbps NRZ-OOK UWOC system is practically demonstrated with a two-stage injection-locked technique to increase the frequency response and a laser beam expander to expand the collimated beam diameter. A 680-nm red-light VCSEL transmitter is adopted in this proposed 5 m/25 Gbps UWOC system, instead of a 450-nm blue-light LD transmitter or a 520-nm green-light LD transmitter. Low BER value and clear eye diagram are achieved in real-time over a 5-m highly turbid harbor water link. Such a proposed UWOC system is a promising alternative for the evolution of optical-based underwater communications, it would be attractive for providing high-speed underwater transmissions.

References

[1] T. C. Wu, Y. C. Chi, H. Y. Wang, C. T. Tsai, and G. R. Lin, “Blue laser diode enables underwater communication at 12.4 Gbps,” *Sci. Rep.*, vol. 7, 2017, Art. no. 40480.
[2] Y. Chen *et al.*, “26 m/5.5 Gbps air-water optical wireless communication based on an OFDM-modulated 520-nm laser diode,” *Opt. Exp.*, vol. 25, no. 13, pp. 14760–14765, 2017.
[3] H. H. Lu *et al.*, “An 8 m/9.6 Gbps underwater wireless optical communication system,” *IEEE Photon. J.*, vol. 8, no. 5, Oct. 2016, Art. no. 7906107.
[4] C. Y. Li *et al.*, “A 16 Gb/s PAM4 UWOC system based on 488-nm LD with light injection and optoelectronic feedback techniques,” *Opt. Exp.*, vol. 25, no. 10, pp. 11598–11605, 2017.
[5] X. Liu *et al.*, “34.5 m underwater optical wireless communication with 2.70 Gbps data rate based on a green laser diode with NRZ-OOK modulation,” *Opt. Exp.*, vol. 25, no. 22, pp. 27937–27947, 2017.
[6] C. Shen *et al.*, “20-meter underwater wireless optical communication link with 1.5 Gbps data rate,” *Opt. Exp.*, vol. 24, no. 22, pp. 25502–25509, 2016.
[7] H. M. Oubei, C. Li, K. H. Park, T. K. Ng, M. S. Alouini, and B. S. Ooi, “2.3 Gbit/s underwater wireless optical communications using directly modulated 520 nm laser diode,” *Opt. Exp.*, vol. 23, no. 16, pp. 20743–20748, 2015.
[8] H. H. Lu *et al.*, “10 m/25 Gbps LiFi transmission system based on a two-stage injection-locked 680 nm VCSEL transmitter,” *Opt. Lett.*, vol. 40, no. 19, pp. 4563–4566, 2015.
[9] H. M. Oubei, R. T. ElAfandy, K. H. Park, T. K. Ng, M. S. Alouini, and B. S. Ooi, “Performance evaluation of underwater wireless optical communications links in the presence of different air bubble populations,” *IEEE Photon. J.*, vol. 9, no. 2, Mar. 2017, Art. no. 7903009.
[10] J. Xu *et al.*, “Underwater wireless transmission of high-speed QAM-OFDM signals using a compact red-light laser,” *Opt. Exp.*, vol. 24, no. 8, pp. 8097–8109, 2016.
[11] A. Albert and C. D. Mobley, “An analytical model for subsurface irradiance and remote sensing reflectance in deep and shallow case-2 waters,” *Opt. Exp.*, vol. 11, no. 22, pp. 2873–2890, 2003.
[12] L. Prieur and S. Sathyendranath, “An optical classification of coastal and oceanic waters based on the specific spectral absorption curves of phytoplankton pigments, dissolved organic matter, and other particulate materials,” *Limnol. Ocean.*, vol. 26, no. 4, pp. 671–689, 1981.
[13] S. Tang, Y. Dong, and X. Zhang, “On link misalignment for underwater wireless optical communications,” *IEEE Commun. Lett.*, vol. 16, no. 10, pp. 1688–1690, Oct. 2012.
[14] B. M. Cochenour, L. J. Mullen, and A. E. Laux, “Characterization of the beam-spread function for underwater optical communications links,” *IEEE J. Ocean. Eng.*, vol. 33, no. 4, pp. 513–521, 2008.