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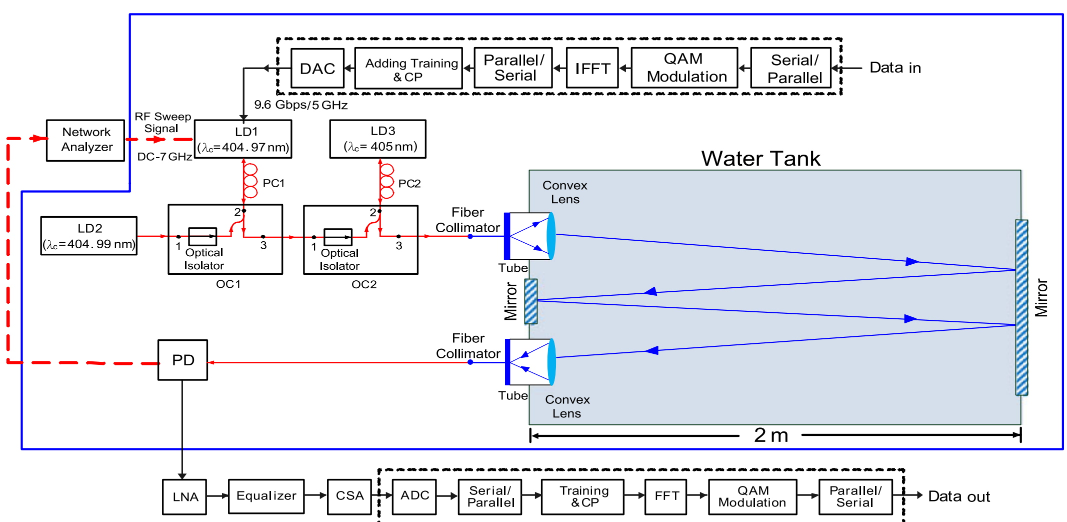

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An 8 m/9.6 Gbps Underwater Wireless Optical Communication System

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Abstract: An 8 m/9.6 Gbps underwater wireless optical communication (UWOC) system based on a two-stage injection-locked 405 nm blue light laser diode (LD) transmitter with a 16-quadrature amplitude modulation (QAM)-orthogonal frequency-division multiplexing (OFDM) modulating signal is proposed and experimentally demonstrated. To the best of our knowledge, it is the first one that employs a two-stage injection-locked technique to improve the transmission performance of UWOC systems. With the assistance of an equalizer at the receiver site, acceptable bit error rate (BER) performance and a constellation map are obtained over an 8-m underwater link. Such a two-stage injection-locked 405 nm blue light LD transmitter-based UWOC system is shown to be a promising alternative, presenting its feasibility for long-range and high-speed underwater links.

Index Terms: Quadrature-amplitude modulation (QAM)-orthogonal frequency-division multiplexing (OFDM), fiber collimator, two-stage injection-locked technique, underwater wireless optical communication.

1. Introduction

In recent years, underwater wireless optical communication (UWOC) has attracted much attention as it can provide a high transmission rate [1]–[6]. Compared to radio-frequency (RF) and acoustic communications, UWOC has a much higher transmission bandwidth, and thus providing much higher transmission rate. Many applications of UWOC systems have been proposed for environmental monitoring, underwater oil pipe investigation, and offshore exploration. With the rapid progress of UWOC systems, the increasing requirements raise the needs for long-range and high-speed underwater links. For an effective implementation of UWOC systems, long underwater link and high underwater transmission rate are the key concerns of system designers. Blue light around the 405 nm band is barely absorbed in the water. An UWOC system employing 405 nm blue light laser diode (LD) is therefore expected to provide a long underwater link. Two-stage injection-locked technique has been used in a two-way passive optical network [7] and a 10 m/25 Gbps light-based WiFi (LiFi) transmission system [8] to improve the transmission performance. However, it has not been used as a system performance improvement scheme in an UWOC system. Two-stage injection-locked technique, which can greatly enhance the frequency response of LD, is therefore expected

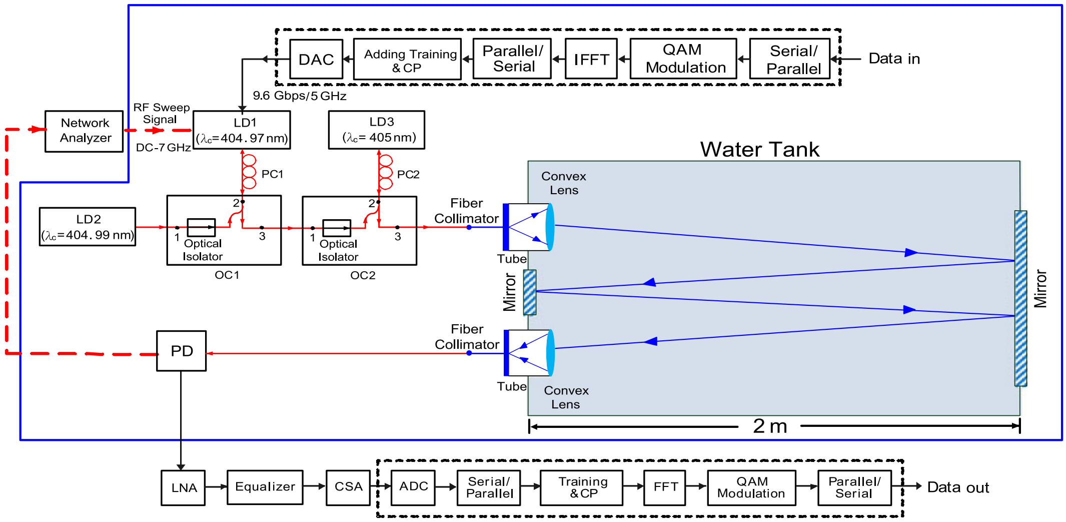

Fig. 1. Experimental configuration of our proposed 8 m/9.6 Gbps UWOC system that employs a two-stage injection-locked 405 nm blue light LD transmitter with 16-QAM-OFDM modulating signal over an 8-m underwater link.

to provide a high transmission rate in UWOC systems. In this paper, an 8 m/9.6 Gbps UWOC system based on a two-stage injection-locked 405 nm blue light LD transmitter with 16-quadrature amplitude modulation (QAM)-orthogonal frequency-division multiplexing (OFDM) modulating signal is proposed and experimentally demonstrated. OFDM is an approach of digital modulation in which a signal is divided into several narrowband channels on multiple carriers. It is an effective technology which has very high spectrum efficiency and robust dispersion tolerance [9]. As far as we know, it is the first one that employs a two-stage injection-locked 405 nm blue light LD transmitter in an UWOC system. Over an 8-m underwater link, acceptable bit error rate (BER) performance and constellation map are achieved in the proposed UWOC systems. Previous study has demonstrated a 7 m/2.3 Gbps UWOC system using on-off keying non-return-to-zero modulation scheme [2]. However, the transmission rate of 2.3 Gbps is much less than 9.6 Gbps of our proposed UWOC systems. Furthermore, a 5.4 m/4.8 Gbps UWOC system has been illustrated formerly [1]. Nevertheless, the transmission distance of 5.4 m and the transmission rate of 4.8 Gbps are less than 8 m and 9.6 Gbps of our proposed UWOC systems. Such proposed two-stage injection-locked 405 nm blue light LD transmitter-based UWOC system is shown to be a potential one to present its feasibility for long-range and high-speed underwater communications.

2. Experimental Setup

The experimental configuration of our proposed 8 m/9.6 Gbps UWOC systems that employs a two-stage injection-locked 405 nm blue light LD transmitter with 16-QAM-OFDM modulating signal over an 8-m underwater link is shown in Fig. 1. LD2 (Thorlabs LP405-SF30, single-mode fiber-pigtailed LD), with a central wavelength of 404.99 nm, is employed as the master laser. LD1, with a central wavelength of 404.97 nm, is employed as the slave laser. The optical output of LD2, with an injection power of 30 mW, is injected into LD1 via an optical circulator (OC1) and a polarization controller (PC1). The OC is composed of a 405-nm optical isolator (Thorlabs IO-5-405-LP) and a 1×2 optical splitter. LD1 is directly modulated by a 9.6 Gbps/5 GHz 16-QAM-OFDM data signal. Meanwhile, LD3, with a central wavelength of 405 nm, is injection-locked by LD1 via OC2 and PC2. All LDs (LD1, LD2, and LD3) have the same optical characteristics. The frequency response of the two-stage injection-locked 405-nm LD transmitter is measured at the port 3 of OC2 by using an optical network analyzer. The 16-QAM-OFDM data signal is generated offline by MATLAB program and uploaded into an arbitrary waveform generator (Tektronix 70001A). Such 16-QAM-OFDM data signal is represented by 256 subcarriers, 512 FFT size, 4.8 G samples per second, and 5 GHz intermediate frequency, respectively. The light emitted from the fiber collimator at the transmitter site is fed into the convex lens, transmitted and reflected four times in the water, inputted into the convex lens, and focused on the fiber collimator at the receiver site. A pair of fiber collimators is utilized to collimate laser light from a fiber to form a collimated optical beam and to guide a collimated optical beam into an optical fiber. The fiber collimators connected to fibers play important roles in forming an optical beam to deliver optical signal through the underwater channel between the transmitter site and the receiver site. The fiber collimator (Thorlabs F671APC-405, FC/APC fiber collimation package) has an operating wavelength range of 395–415 nm, a collimated beam diameter of 0.7 mm, and a focal length of 4.02 mm. The function of the convex lens (Thorlabs LB1761-A, bi-convex lenses) at the transmitter site is to produce a parallel optical beam, and the function of the convex lens at the receiver site is to couple the parallel optical beam into a point. The dimensions of the water tank are 2 m $\times$ 1.4 m $\times$ 0.7 m. The light transmission distance passing through the water tank is extended up to 8 m (2 m $\times$ 4) by using mirrors at both sides of water tank. The water tank is filled with piped water with an attenuation coefficient of 0.074 m^{-1} [10]. Over a 8-m underwater link, the modulated light is reached to a photodiode (PD). The PD (imm photonics, high-speed photodiode 320-1000 nm) has a 3-dB bandwidth of 6 GHz, a detection wavelength range of 320-1000 nm, an active area diameter of 0.4 mm, and a responsivity of around 0.24 mA/mW (at 405 nm). The received signal is then amplified by a low noise amplifier (LNA) and passed through an equalizer (Astra Microwave, AMT1753011) for equalization. The LNA (Nextec Microwave & RF, NBL00419) has a frequency range of 4-8 GHz, a small signal gain of about 30 dB, and a low noise figure of around 1.7 dB (measured at 5 GHz). Since it is difficult to have an avalanche PD (APD) with a 3-dB bandwidth larger than 5 GHz, yet a PD with a 3-dB bandwidth of 6 GHz and a LNA with a small signal gain of 30 dB are utilized to substitute an APD. Finally, the 16-QAM-OFDM signal is analyzed by an OFDM analyzer, captured by a communication signal analyzer (CSA), and processed off-line with a MATLAB program to analyze the BER performance and corresponding constellation map.

In addition, the measurement of the frequency response of the 405 nm blue light LD transmitter-based UWOC systems is also illustrated in Fig. 1. RF sweep signal (DC – 7 GHz) generated from a network analyzer is fed into the LD1. After PD detection, the detected RF sweep signal is fed into a network analyzer. Thus, the frequency response of the 405 nm blue light LD transmitter-based UWOC systems is measured under the scenarios of free-running, one-stage injection locking, and two-stage injection locking.

3. Experimental Results and Discussion

The output optical power of LD1 at different operation currents is presented in Fig. 2(a). It is obvious that as the operation current is 85.3 mA, the maximum optical power of 30 mW is obtained. The overall light attenuation effects of absorption and scattering in underwater environment can be stated as [11]

$$\mathbf{I} = \mathbf{I}_0 \mathbf{e}^{-c(\lambda)z} \tag{1}$$

where I_0 is the optical power of transmitted light, z denotes the light transmission distance, I represents the optical power of light after transmitting z distance, and $c(\lambda)$ stands for the overall attenuation coefficient. The exact value of the overall attenuation coefficient $c(\lambda)$ will change with different water types and water depth. The $c(\lambda)$ can be expressed as

$$c(\lambda) = a(\lambda) + b(\lambda) \tag{2}$$

where $a(\lambda)$ is the term related to the absorption of water, and $b(\lambda)$ is the term related to the scattering of water. The $a(\lambda)$ can be further presented as the summation of four absorption factors:

$$a(\lambda) = a_w(\lambda) + a_{CDOM}(\lambda) + a_{phy}(\lambda) + a_{det}(\lambda) \tag{3}$$

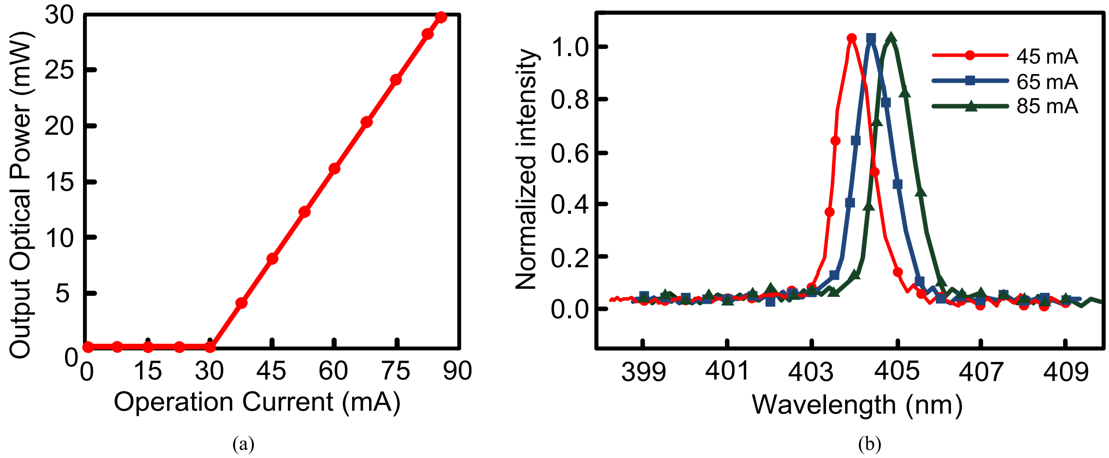

Fig. 2. (a) Output optical power of LD1 at different operation currents and (b) measured optical spectra at 25 °C under different operation currents.

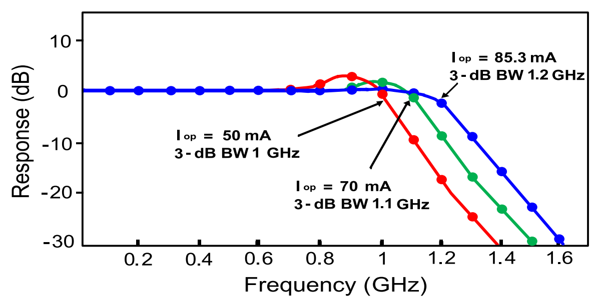

Fig. 3. Frequency response of the free-running LD1.

where $a_w(\lambda)$ is the absorption due to pure water, $a_{CDOM}(\lambda)$ is the absorption due to colored dissolved organic materials (CDOM), $a_{phy}(\lambda)$ is the absorption due to phytoplankton, and $a_{det}(\lambda)$ is the absorption due to detritus. Furthermore, the $b(\lambda)$ can be further presented as the summation of three scattering factors:

$$b(\lambda) = b_w(\lambda) + b_{phy}(\lambda) + b_{det}(\lambda) \quad (4)$$

where $b_w(\lambda)$ is the scattering due to pure water, $b_{phy}(\lambda)$ is the scattering due to phytoplankton, and $b_{det}(\lambda)$ is the scattering due to detritus. Compared with absorption, scattering is relatively independent of wavelength. The dominant factor that impacts scattering is the density of particulate matters. In piped water, absorption is the main limiting factor, the low scattering coefficient makes the beam free from divergence. In ocean water, there is a higher concentration of dissolved particles that affects scattering. Turbid water has the highest concentration of dissolved matters, which will severely attenuate the light propagation. From (1), it is clear that as the light transmission distance increases, the optical power of light after transmitting z distance decreases. In order to have a maximum light transmission distance in the water, the operation current of LD1 is set at 85.3 mA. In addition, the measured optical spectra at 25 °C under different operation currents are presented in Fig. 2(b). The peak emission wavelength is around 404.14 nm for the blue LD operated at 45 mA and is slightly red-shifted with increasing operation current.

The frequency response of the free-running LD1 is shown in Fig. 3. As the operation current (I_{op}) is operated at 50 mA, the 3 dB bandwidth is 1 GHz. As the operation current is operated at 85.3 mA, however, the 3 dB bandwidth is increased up to 1.2 GHz. It can be concluded that, from Figs. 2(a) and 3, as the operation current is 85.3 mA, not only maximum optical power of 30 mW is obtained, but extended 3-dB bandwidth of 1.2 GHz is also achieved. It indicates that such a

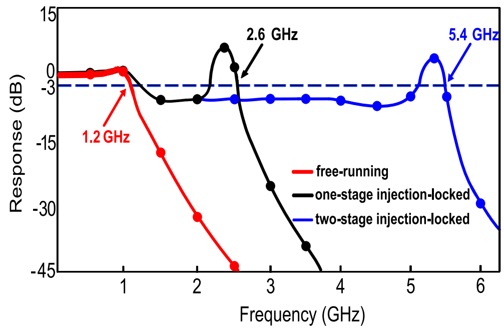

Fig. 4. Frequency response of the 405-nm blue light LD-based UWOC systems for free-running, one-stage injection locking, and two-stage injection locking scenarios.

405-nm blue light LD is designed for qualified use in UWOC systems. The optical output power of LD increases with an increase in the underwater link. A LD is operated as high as possible to obtain high optical output power and long underwater link simultaneously. Nevertheless, as the operation current is increased, the optical modulation index (OMI) of LD is decreased, and consequently, the carrier-to-noise ratio (CNR) of the received 16-QAM-OFDM signal is degraded. Although the format of 9.6 Gbps/5 GHz 16-QAM-OFDM data signal is a RF passband format; however, the format of 9.6 Gbps data stream is a digital baseband format. Since the digital signal is in more robust than analog signal with respect to noise, yet a 9.6-Gbps data stream has a high tolerance to noise. Thereby, high output optical power of LD is worth obtaining due to high tolerance to noise for 9.6 Gbps digital baseband signal.

The frequency response of the 405-nm blue light LD-based UWOC systems for free-running, one-stage injection locking, and two-stage injection locking scenarios are presented in Fig. 4. At an operation current of 85.3 mA, for free-running scenario, the 3-dB bandwidth is 1.2 GHz; for one-stage injection locking scenario, the 3-dB bandwidth is 2.6 GHz; for two-stage injection locking scenario, the 3-dB bandwidth is increased up to 5.4 GHz, as expected. This finding shows that the two-stage injection-locked 405 nm blue light LD transmitter is strong enough for 9.6 Gbps/5 GHz 16-QAM-OFDM signal transmission. To obtain a high 3-dB bandwidth, the wavelengths of the injected lights must be carefully chosen to obtain the optimum enhancement in the frequency response of the two-stage injection-locked 405-nm blue light LD. For one-stage injection locking scenario, the wavelength of the master laser (LD2) should be slightly longer than that of the slave laser (LD1) to achieve a flat frequency response; that is, positive wavelength detuning is employed to complete the one-stage injection locking. For two-stage injection locking scenario, however, the wavelength of the master laser (one-stage injection-locked LD1) should be slightly shorter than that of the slave laser (LD3) to achieve a high-frequency resonance peak, that is, negative wavelength detuning is employed to complete the second-stage injection locking [7].

The resonance frequency of the injection-locked LD () is given by [12]

$$\omega_R^2 \approx \omega_{R0}^2 + k^2 \left(\frac{A_{inj}}{A_0}\right)^2 \sin^2\varphi_0 \tag{5}$$

where ω_{R0} is the relaxation oscillation frequency of the free-running slave laser, k is the coupling coefficient, A_{inj}/A_0 is the injection ratio, and φ_0 is the steady-state phase difference between the injection-locked slave laser and the master laser. From (5), it can be seen that increasing the injection ratio will enhance the resonance frequency. A 405-nm blue light LD-based UWOC systems employing two-stage injection-locked technique can be demonstrated to significantly enhance the resonance frequency of the LD, as long as the master LD has enough optical power to inject into the slave LD in each stage. As optimum two-stage injection locking happens, the 405-nm blue light LD-based UWOC systems have the best transmission performances in terms of the lowest BER value and the clearest constellation map.

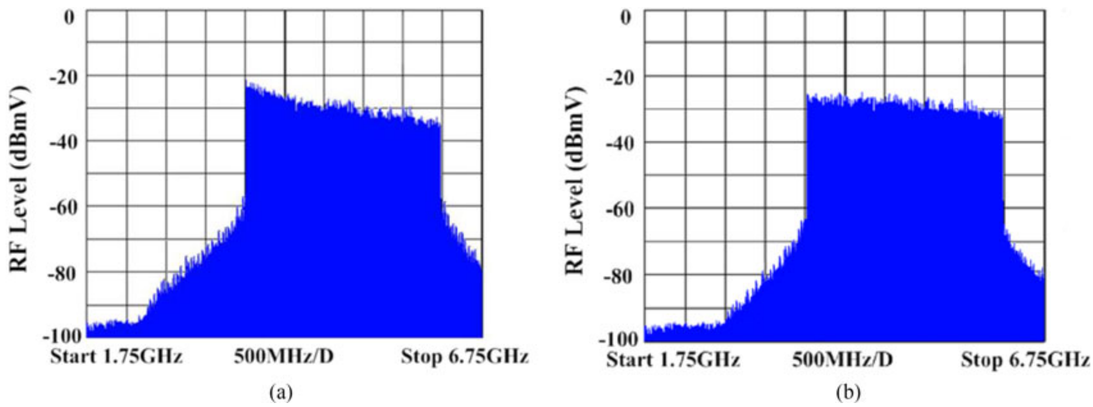

Fig. 5. Electrical spectra of the 9.6 Gbps/5 GHz 16-QAM-OFDM data signal (a) before an equalizer and (b) after an equalizer.

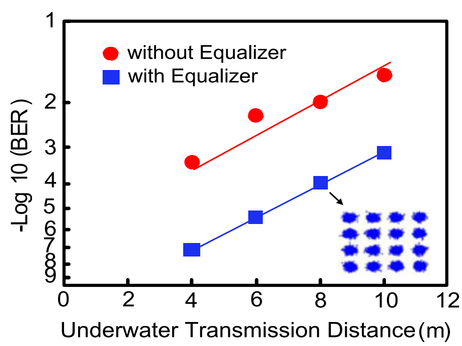

Fig. 6. Measured BER curves and constellation map at a data signal of 9.6 Gbps/5 GHz.

Fig. 5(a) and (b) show the electrical spectra of the 9.6 Gbps/5 GHz 16-QAM-OFDM data signal before and after an equalizer. For 9.6 Gbps/5 GHz 16-QAM-OFDM data signal, it has a bandwidth of 2.5 GHz; it indicates that the lowest frequency of 9.6 Gbps/5 GHz 16-QAM-OFDM data signal is 3.75 GHz ($5 - 2.5/2 = 3.75$), and the highest frequency of 9.6 Gbps/5 GHz 16-QAM-OFDM data signal is 6.25 GHz ($5 + 2.5/2 = 6.25$). Clearly, the frequency response of the 9.6 Gbps/5 GHz 16-QAM-OFDM data signal is compensated around 10 dB after through an equalizer. The equalizer is used to render the frequency response. When the signal has been equalized, the frequency domain attributes of the signal at the input are expected to faithfully reproduce at the output. The electrical spectrum of the 9.6 Gbps/5 GHz 16-QAM-OFDM data signal after an equalizer is more flat than that before an equalizer. The better flat electrical spectrum we obtain in UWOC systems, the better transmission performance we achieve in UWOC systems.

To analyze the transmitted 16-QAM-OFDM signal performance, the measured BER curves and constellation map at a data signal of 9.6 Gbps/5 GHz are presented in Fig. 6. Over an 8-m underwater link; without employing equalizer, the BER is about 10^{-2}; with employing equalizer, the BER is reached about 10^{-4}, which is well below the forward error correction (FEC) limit criterion of 3.8×10^{-3}. As equalizer is employed, acceptable BER value and constellation map are achieved to demonstrate the feasibility of establishing an 8 m/9.6 Gbps UWOC system based on a two-stage injection-locked 405 nm blue light LD transmitter.

The UWOC system is to realize the underwater transmission using a pair of fiber collimators with fibers. Propagating an optical beam through the underwater channel between the fiber collimator enacts the UWOC system to work as if the fibers were connected seamlessly. Optical beam alignment and focal spot size between the convex lens and the fiber collimator at the receiver site is critical for the transmission performance of UWOC systems. The transmission performance of UWOC systems will be degraded if large optical beam misalignment and divergent focal spot size occur. To guarantee a successful design of UWOC systems, the system designer will have to emphasize the optimum optical beam alignment and focal spot size between the convex lens and the fiber collimator at the receiver site.

To achieve a high transmission rate, we can also use space-division-multiplexing (SDM) scheme with multiple blue LDs that carry multiple independent parallel data streams. Each underwater link employs a laser beam to establish an independent optical link. If each blue LD would carry its data stream, then there would be interference and crosstalk that arises from the adjacent channels. Such interference and crosstalk will lead to a serious BER performance degradation. Moreover, multiple signal generators would be needed to establish such an SDM UWOC system. These multiple signal generators will increase the cost of the SDM UWOC systems. For a practical implementation of UWOC systems, it is necessary to develop a configuration with potentially economic advantage. Therefore, two-stage injection-locked technique is worth employing in UWOC systems for providing better transmission performance and cost-effective advantage.

4. Conclusion

An 8 m/9.6 Gbps UWOC system that employs a two-stage injection-locked 405 nm blue light LD transmitter with 16-QAM-OFDM modulating signal is proposed and experimentally demonstrated. As far as we know, it is the first one that employs two-stage injection-locked technique to improve the transmission performance of UWOC systems. Acceptable BER performance and constellation map are achieved in the proposed 8 m/9.6 Gbps UWOC systems. Two-stage injection-locked technique is worth employing because the performance of 405 nm blue light LD can be improved not only with higher 3 dB bandwidth but with lower threshold current as well. Such an innovative UWOC system provides the advantages of underwater link for long transmission distance and high transmission rate, which is an attractive feature that can accelerate UWOC deployment.

References

[1] H. M. Oubei *et al.*, "4.8 Gbit/s 16-QAM-OFDM transmission based on compact 450-nm laser for underwater wireless optical communication," *Opt. Exp.*, vol. 23, no. 18, pp. 23302–23309, 2015.

[2] 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.

[3] K. Nakamura, I. Mizukoshi, and M. Hanawa, "Optical wireless transmission of 405 nm, 1.45 Gbit/s optical IM/DD-OFDM signals through a 4.8 m underwater channel," *Opt. Exp.*, vol. 23, no. 2, pp. 1558–1566, 2015.

[4] W. Cox and J. Muth, "Simulating channel losses in an underwater optical communication system," *J. Opt. Soc. Amer. A*, vol. 31, no. 5, pp. 920–934, 2014.

[5] C. Gabriel, M. Khalighi, S. Bourennane, P. Léon, and V. Rigaud, "Monte-Carlo-based channel characterization for underwater optical communication systems," *J. Opt. Commun. Netw.*, vol. 5, no. 1, pp. 1–12, 2013.

[6] S. Arnon, "Underwater optical wireless communication network," *Opt. Eng.* vol. 49, no. 1, 2010, Art. no. 015001.

[7] C. L. Ying, H. H. Lu, C. Y. Li, C. Y. Lin, C. Y. Lin, and P. C. Peng, "A 20-km/60-Gb/s two-way PON based on directly modulated two-stage injection-locked 1.55-μm VCSELs transmitters and negative dispersion fibers," *IEEE Photon. J.*, vol. 7, no. 1, Feb. 2015, Art. no. 7200409.

[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] C. Y. Lin, *et al.*, "A hybrid CATV/16-QAM-OFDM in-house network over SMF and GI-POF/VLC transport," *IEEE Photon. Technol. Lett.* vol. 27, no. 5, pp. 526–529, Mar. 2015.

[10] J. W. Giles and I. N. Bankman, "Underwater optical communications systems. Part 2, Basic design considerations," in *Proc. IEEE Mil. Commun. Conf.*, 2005, vol. 3, pp. 1700–1705.

[11] C. D. Mobley *et al.*, "Comparison of numerical models for computing underwater light fields," *Appl. Opt.* vol. 32, no. 36, pp. 7484–7504, 1993.

[12] A. Murakami, K. Kawashima, and K. Atsuki, "Cavity resonance shift and bandwidth enhancement in semiconductor lasers with strong light injection," *IEEE J. Quantum Electron.* vol. 39, no. 10, pp. 1196–1204, Oct. 2003.