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500 Gb/s PAM4 FSO-UWOC Convergent System With a R/G/B Five-Wavelength Polarization-Multiplexing Scheme

WEN-SHING TSAI[1], HAI-HAN LU[2], (Senior Member, IEEE), HSIAO-WEN WU[3], SHI-CHENG TU[2], YONG-CHENG HUANG[2], JING-YAN XIE[2], QI-PING HUANG[2], AND SONG-EN TSAI[2]

[1]Department of Electrical Engineering, Ming Chi University of Technology, New Taipei City 243, Taiwan
[2]Institute of Electro-Optical Engineering, National Taipei University of Technology, Taipei 106, Taiwan
[3]Department of Electronic Engineering, Tungnan University, New Taipei City 222, Taiwan

Corresponding author: Hai-Han Lu (hhlu@ntut.edu.tw)

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ABSTRACT A 500-Gb/s four-level pulse amplitude modulation (PAM4) free-space optical (FSO)-underwater wireless laser transmission (UWOC) convergent system over 100 m free-space transmission with either 10 m piped underwater link or 5 m turbid underwater link is established, employing a red/green/blue (R/G/B) five-wavelength polarization-multiplexing scheme as a demonstration for the first time. Integrating PAM4 modulation with five-wavelength polarization-multiplexing scheme, the channel capacity of FSO-UWOC convergent systems is significantly increased with an aggregate data rate of 500 Gb/s [50 Gb/s PAM4/wavelength × 5 wavelengths × 2 polarizations (*p*- and *s*-polarizations)]. Results reveal that five R/G/B laser diode (LD) transmitters with two-stage light injection and optoelectronic feedback techniques are capably adopted for 500 Gb/s PAM4 signal transmission. Compared with prior FSO-UWOC convergence and visible light communication using polarization-multiplexing R/G/B LDs, it shows a prominent one with the benefits of high aggregate transmission rate and long-range optical wireless link. Excellent bit error rate performance and accepted PAM4 eye diagrams are attained over a 110-m/105-m FSO-UWOC link. This demonstrated five-wavelength polarization-multiplexing FSO-UWOC convergent system is promising because it not only integrates free-space backbone with underwater optical wireless feeder, but it also substantially multiplies total channel capacity.

INDEX TERMS Five-wavelength, FSO-UWOC convergent system, PAM4 modulation, polarization-multiplexing scheme, R/G/B LD.

I. INTRODUCTION

Free-space optical (FSO)-underwater wireless optical communication (UWOC) convergent system is a promising one to conquer the connectivity difficulties [1]–[4]. It is an attractive convergence that has a number of advantages, such as license-free propagation, reuse of atmospherical/underwater operating bandwidths, high directionality, and no electromagnetic interference. With the fast enhancement of FSO-UWOC convergence, an increasing request pushes the requirements for building an FSO-UWOC convergent system with high-transmission-rate and improved spectral efficiency. Polarization-multiplexing scheme has been investigated for supplying high channel capacity [5]–[7], it thoroughly fits the configuration of FSO-UWOC convergent system. With polarization-multiplexing scheme, the channel capacity of FSO-UWOC convergence can be largely increased. Moreover, to further improve the channel capacity and spectral efficiency, four-level pulse amplitude modulation (PAM4) instead of none-return-to-zero modulation is adopted to reach the goal of high-transmission-rate and enhanced spectral efficiency [8]–[10]. In this study, a 500-Gb/s PAM4 FSO-UWOC convergent system through 100 m free-space transmission with either 10 m piped underwater link or 5 m turbid underwater link is proposed, employing a red/green/blue (R/G/B) five-wavelength

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polarization-multiplexing scheme as an illustration. In piped underwater links, the overall attenuation coefficients at 450.6 nm (blue-light), 488.2 nm (blue-light), and 520.4 nm (green-light) are lower than those at 642.6 nm and 660.3 nm (red-light) [11]–[14]. 450.6 nm blue-light, 488.2 nm blue-light, and 520.4 nm green-light laser diode (LD) with two-stage light injection and optoelectronic feedback techniques are thereby utilized in a 110-m FSO-UWOC convergence. Whereas in turbid underwater links, the overall attenuation coefficients at 642.6 nm and 660.3 nm (red-light) are lower than those at 450.6 nm (blue-light), 488.2 nm (blue-light), and 520.4 nm (green-light) [15]–[17]. 642.6 nm and 660.3 nm red-light LD with two-stage light injection and optoelectronic feedback techniques are thereby utilized in a 105-m FSO-UWOC convergence. LD with two-stage light injection and optoelectronic feedback techniques integrates the optical properties and advantages of LD and directs a promising way of high-bandwidth operation, in which LDs' 3-dB bandwidth can be considerably enhanced [18]. Given that five wavelengths with *p*- and *s*-polarizations are multiplexed, five-wavelength polarization-multiplexing scheme enhances the channel capacity ten times. The total channel capacity of FSO-UWOC convergent system is considerably multiplied, by a factor of twenty, via the utilization of PAM4 modulation and R/G/B five-wavelength polarization multiplexing scheme [2 (PAM4 modulation) $\times$ 5 (R/G/B five-wavelength) $\times$ 2 (polarization-multiplexing) = 20]. To the author's understanding, this demonstration is the leading one that efficaciously builds a R/G/B PAM4 FSO-UWOC convergent system with a total transmission rate of 500 Gb/s. With the implementation of doublet lenses in FSO communications [19]–[21] and laser beam reducer/expander in UWOC links, excellent bit error rate (BER) performance and accepted PAM4 eye diagrams are attained in such demonstrated FSO-UWOC convergent system. Our former work built a 256-Gb/s PAM4 FSO-UWOC convergent system with a four-channel space-division-multiplexing (SDM) scheme [1]. However, four sets of doublet lenses are envisioned to build such complex and costly four-channel SDM FSO-UWOC convergent system. For an actual realization, it is critically important to build an FSO-UWOC convergence with low-complexity and low-cost advantages. Additionally, the total channel capacity and the FSO-UWOC link of 256 Gb/s and 55 m are considerably less than the associated values of 500 Gb/s and 110/105 m operated in this proposal. As for optical wireless communication with R/G/B multi-wavelength polarization-multiplexing scheme, Wei *et al*. achieved a 40-Gb/s visible light communication (VLC) adopting polarization-multiplexing R/G/B LDs [22]. Nevertheless, the aggregate transmission capacity and the free-space link of 40 Gb/s and 2 m are far less than the corresponding ones of 500 Gb/s and 100 m operated in this proposed convergence.

We realistically build a PAM4 FSO-UWOC convergent system with a R/G/B five-wavelength polarization-multiplexing scheme. It outperforms former FSO-UWOC convergence and VLC given its traits for providing high aggregate channel capacity with long-reach optical-based free-space and underwater transmissions. The contributions of this study can be summarized as follows:

(I) A R/G/B PAM4 FSO-UWOC convergence with an aggregate transmission rate of 500 Gb/s is attained.
(II) Combining PAM4 modulation with R/G/B five-wavelength polarization-multiplexing scheme, the total channel capacity is significantly enhanced by a factor of twenty.
(III) A long-reach 100 m free-space transmission with either 10 m piped underwater link or 5 m turbid underwater link is achieved.
(IV) Significant 3-dB bandwidth improvement is acquired by utilizing blue-/green-/red-light LD with two-stage light injection and optoelectronic feedback techniques.
(V) Employing a set of doublet lenses in FSO communications and a laser reducer/expander in UWOC links, a sufficient low BER of 10^{-9} and qualified PAM4 eye diagrams are obtained.

II. EXPERIMENTAL SETUP

The configuration of illustrated 500 Gb/s PAM4 FSO-UWOC convergent system with a R/G/B five-wavelength polarization-multiplexing scheme over 100 m free-space transmission with either 10 m piped underwater link or 5 m turbid underwater link is presented in the Fig. 1. After amplification and linearization by a linear driver, a 50-Gb/s PAM4 signal generated from a PAM4 generator is separated and fed into blue-light LD1 (with 450.6 nm central wavelength), blue-light LD4 (with 488.2 nm central wavelength), green-light LD7 (with 520.4 nm central wavelength), red-light LD10 (with 642.6 nm central wavelength), and red-light LD13 (with 660.3 nm central wavelength), respectively. If each LD would carry its own modulation, then there should be 10 50-Gb/s PAM4 signal sources if the proposed system could achieve 500 Gb/s capacity. However, a 500-Gb/s PAM4 FSO-UWOC convergence can't be realized in the scenario of LDs with free-running because of LD's insuficient 3-dB bandwidth. LD1's/LD4's/LD7's/LD10's/LD13's output is injected into LD2/LD5/LD8/LD11/LD14 via light injection and optoelectronic feedback techniques. Next, the output of injection-locked LD2/LD5/LD8/LD11/LD14 is injected into LD3/LD6/LD9/LD12/LD15 via second-stage light injection and optoelectronic feedback techniques (as shown in the dashed block diagram of Fig. 1) [18], [23], [24]. In this study, a 50-Gb/s PAM4 signal is applied to the first step master LD (LD1/LD4/LD7/LD10/LD13). If instead of master LD, slave LD (LD3/LD6/LD9/LD12/LD15) is modulated with 50 Gb/s PAM4 signal, there should be a less attenuation of the PAM4 signal [25]. However, the attenuation of the PAM4 signal can be recompensed by the amplification of the linear driver. The performance of FSO-UWOC convergence influenced by low modulation PAM4 signal is limited. Regarding data erasing problem [26], it can be avoided by operating slave LD at moderate DC bias, instead of high DC bias. As the

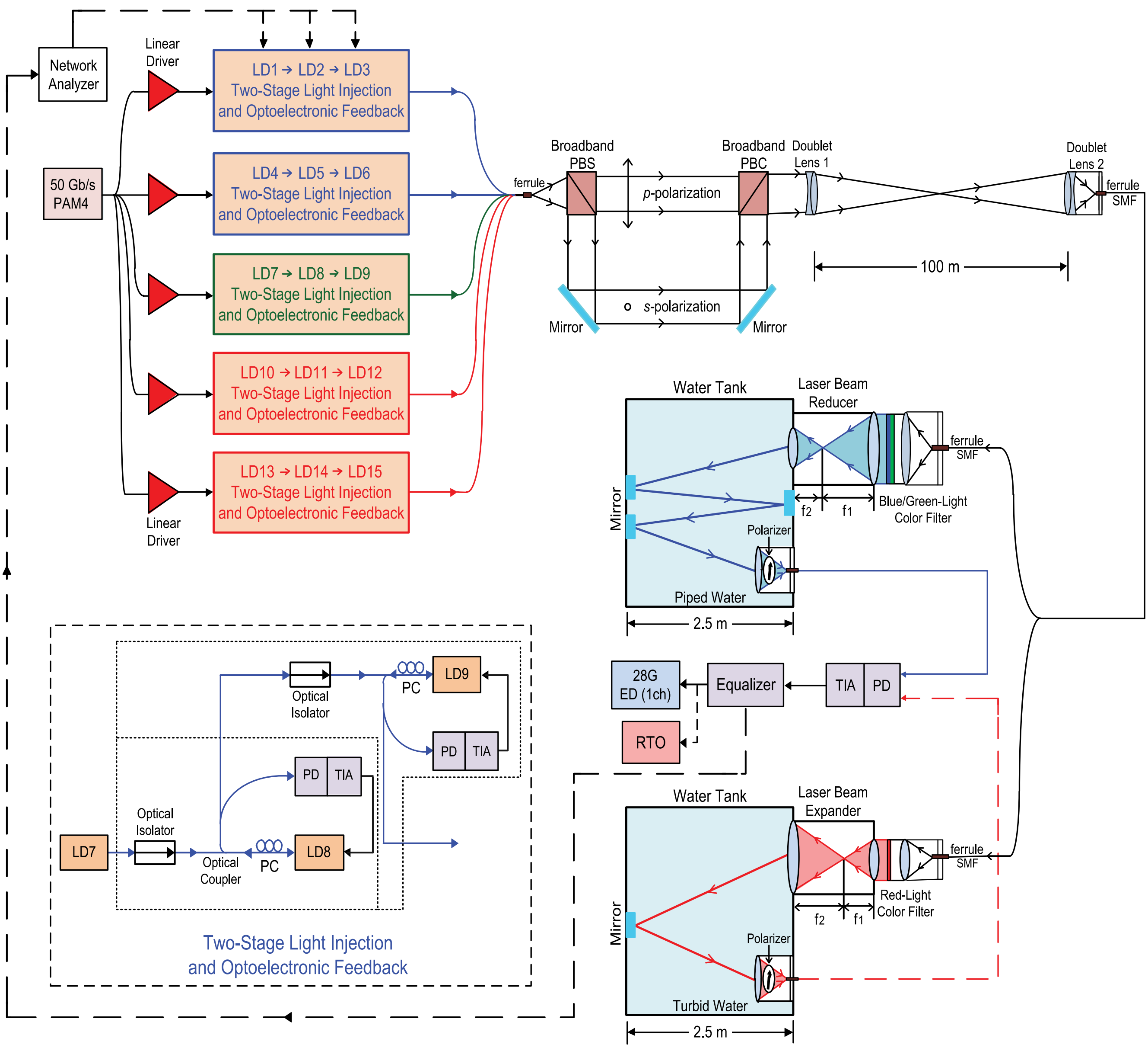

FIGURE 1. **The configuration of illustrated 500 Gb/s PAM4 FSO-UWOC convergent system with a R/G/B five-wavelength polarization-multiplexing scheme over 100 m free-space transmission with either 10 m piped underwater link or 5 m turbid underwater link. PAM4, four-level pulse amplitude modulation; LD, laser diode; PD, photodiode; TIA, trans-impedance amplifier; PBS, polarization beam splitter; PBC, polarization beam combiner; ED, error detector; RTO, real-time oscilloscope.**

slave LD is operated at moderate DC bias, data-suppressing effect under injection locking is small. The laser lights (each light with 50 Gb/s optical PAM4 signal) are then combined using an optical combiner, split into two parts along the two orthogonal polarizations (*p*- and *s*-polarizations) using a broadband polarization beam splitter with a wavelength range of 420-680 nm. Two plane mirrors are placed at a leaning angle to reflect the *s*-polarized light. The *p*-polarized and *s*-polarized lights are then recombined by a broadband polarization beam combiner with a wavelength range of 420-680 nm. Five optical PAM4 signals with *p*- and *s*-polarized lights are then inputted into a 100-m free-space link using a couple of doublet lenses, and split by a 1×2 optical splitter at the receiving site. For upper path, blue-/green-light color filter is utilized to select the wanted wavelength. After wavelength selection, the selected laser beam is supplied in a laser beam reducer, delivered through a 10-m (2.5 m $\times$ 4) piped underwater link, and inputted into a convex lens. For lower path, red-light color filter is utilized to filter the wanted wavelength. After wavelength filtering, the filtered wavelength is supplied in a laser beam expander, transported through 5 m (2.5 m $\times$ 2) turbid underwater link, and sent to a convex lens. Subsequently, a polarizer with adjustable polarization is employed to pick the matching *p*- or *s*-polarized laser light. The drift in the polarization state is a critical issue with the practical use of polarization-multiplexing scheme over UWOC systems. The *p*-polarized and *s*-polarized lights experience different phase velocities

TABLE 1. 3-dB bandwidths for the free-running (LD1/LD4/LD7/LD10/LD13), light injection and optoelectronic feedback (injection-locked LD2/LD5/LD8/LD11/LD14), and two-stage light injection and optoelectronic feedback (injection-locked LD3/LD6/LD9/LD12/LD15) scenarios.

Laser \ State	Free-Running	Light Injection and Optoelectronic Feedback	Two-Stage Light Injection and Optoelectronic Feedback
Blue-Light LD (450.6 nm)	1.82 GHz (LD1)	8.41 GHz (LD1→LD2)	18.41 GHz (LD1→LD2→LD3)
Blue-Light LD (488.2 nm)	1.8 GHz (LD4)	8.36 GHz (LD4→LD5)	18.32 GHz (LD4→LD5→LD6)
Green-Light LD (520.4 nm)	1.78 GHz (LD7)	8.24 GHz (LD7→LD8)	18.26 GHz (LD7→LD8→LD9)
Red-Light LD (642.6 nm)	1.83 GHz (LD10)	8.42 GHz (LD10→LD11)	18.46 GHz (LD10→LD11→LD12)
Red-Light LD (660.3 nm)	1.81 GHz (LD13)	8.38 GHz (LD13→LD14)	18.38 GHz (LD13→LD14→LD15)

and thus have a certain phase difference at the receiving end. Over a long-distance underwater link, the drift in the polarization state will become one of the limiting influences of UWOC systems. It will be somewhat difficult to track the polarization state with disturbed water as well. However, a polarization tracker can be installed to transfer the arbitrary polarization to the settled polarization state [27], [28]. The polarization tracker recovers two orthogonal polarization states to mitigate the polarization state with long-distance underwater link/disturbed water. Given that the underwater link is merely 10 m (piped underwater link)/5 m (turbid underwater link), the drift in the polarization is small and thereby the polarization state is stable in the scenario through 10 m piped underwater link/5 m turbid underwater link. Then, the *p*- or *s*-polarized light is guided into fiber's ferrule and enhanced by a 25-GHz photodiode (PD) with a trans-impedance amplifier (TIA) receiver. The enhanced 50 Gb/s PAM4 signal is then sent to an equalizer for signal equalization. After equalization, a real-time BER measurement is implemented utilizing a high-sensitivity error detector and the PAM4 three-eye sampling method [29]. It is attractive because it avoids the need of complicated off-line digital signal processing using MATLAB. Further, a real-time oscilloscope is utilized to catch the eye diagrams of transmitted 50 Gb/s PAM4 signal.

Fig. 1 shows the frequency response measurement setup of FSO-UWOC convergence as well. A sweep signal (DC – 20 GHz) produced from a network analyzer sends to the blue-/green-/red-light LD. After equalization by an equalizer, the sweep signal returns to the network analyzer. Then, the frequency response of the FSO-UWOC convergent system is measured in the states of free-running (LD1/LD4/LD7/LD10/LD13), light injection and optoelectronic feedback (injection-locked LD2/LD5/LD8/LD11/LD14), and two-stage light injection and optoelectronic feedback (injection-locked LD3/LD6/LD9/LD12/LD15).

III. RESULTS AND DISCUSSIONS

Table 1 exhibit the 3-dB bandwidths for the free-running (LD1/LD4/LD7/LD10/LD13), light injection and optoelectronic feedback (injection-locked LD2/LD5/LD8/LD11/LD14), and two-stage light injection and optoelectronic feedback (injection-locked LD3/LD6/LD9/LD12/LD15) scenarios. With two-stage light injection and optoelectronic feedback techniques, it can be seen that the 3-dB bandwidths are greatly enhanced ∼10 times (1.82 GHz/1.8 GHz/1.78 GHz/1.83 GHz/1.81 GHz → 18.41 GHz/18.32 GHz/18.26 GHz/18.46 GHz/18.38 GHz). These significant enhancements in 3-dB bandwidth reveal that blue-, green-, and red-light LDs with two-stage light injection and optoelectronic feedback techniques are effectual for building a 500-Gb/s PAM4 FSO-UWOC convergent system. With light injection and optoelectronic feedback techniques, the resonance frequency of LD is enhanced. The frequency difference between the injection-locked laser mode and the cavity mode accords with the resonance frequency in the RF domain. Employing light injection and optoelectronic feedback techniques, a difference between the injection-locked laser mode and the cavity mode can be attained, by which bringing on a resonance enhancement and a 3-dB bandwidth improvement. Furthermore, with two-stage light injection and optoelectronic feedback techniques, a larger difference between the injection-locked laser mode and the cavity mode can be acquired, by which leading to a further resonance enhancement and a further 3-dB bandwidth improvement [18].

The optical spectra of five color filters are exhibited in Fig. 2. The blue- and green-light color filters are featured by central wavelengths of 456 nm, 488 nm, and 514.5 nm, respectively; and full width at half maximums (FWHMs) of 22 nm, 24 nm, and 25.7 nm, respectively. As for the red-light color filters, they are featured by central wavelengths of 632.8 nm and 660 nm, respectively; and FWHMs

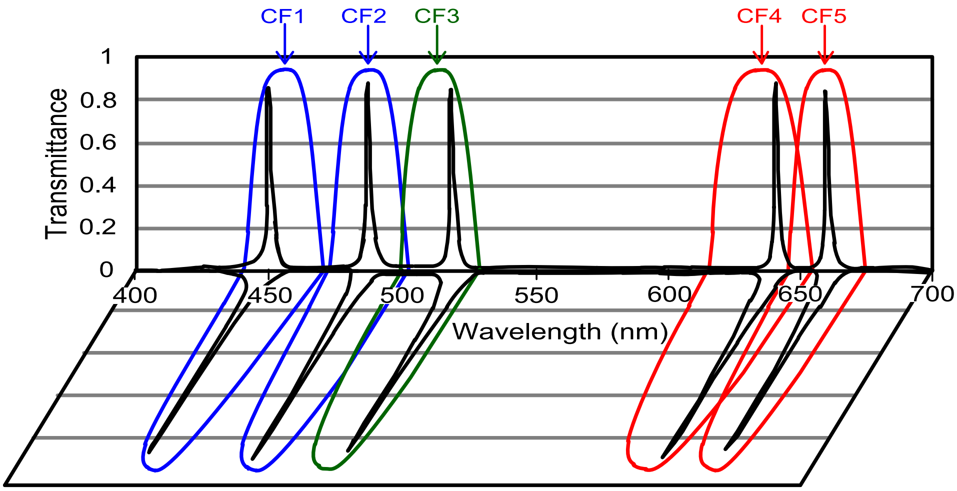

FIGURE 2. The optical spectra of five color filters with central wavelengths of 456, 488, 514.5, 632.8 and 660 nm; and five filtered wavelengths with *p*- and *s*-polarizations and central wavelengths of 450.6, 488.2, 520.4, 642.6, and 660.3 nm.

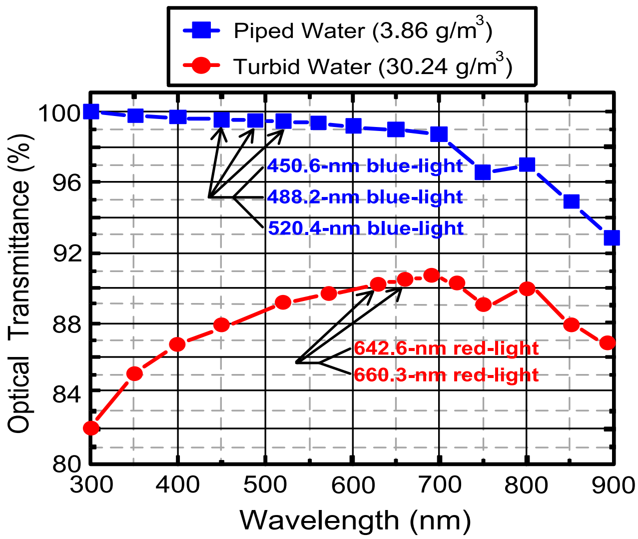

FIGURE 3. The optical transmittance with 0.3 (piped water) and 30.24 g/m^3 (turbid water) particle concentrations.

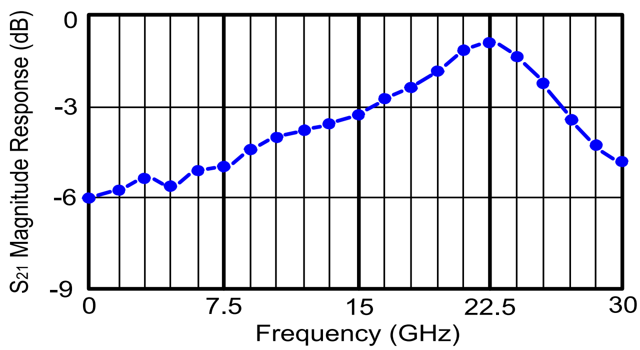

FIGURE 4. The S_{21} magnitude response of the equalizer.

of 31.6 nm and 20 nm, respectively. Besides, the optical spectra of five filtered wavelengths with *p*- and *s*-polarizations are exhibited in Fig. 2 as well. These five filtered wavelengths for directly modulated 50 Gb/s PAM4 signals are 450.6, 488.2, 520.4, 642.6, and 660.3 nm, respectively. Among these five filtered wavelengths, the maximum channel spacing is 122.2 nm (642.6 – 520.4 = 122.2), and the minimum channel spacing is 17.7 nm (660.3 – 642.6 = 17.7). For a small channel spacing of 17.7 nm, a red-light color filter with a central wavelength of 632.8 nm and a large FWHM of 31.6 nm can satisfy the demand to filter the 642.6-nm wavelength and filter out the 660.3-nm wavelength [$642.6 < (632.8 + 31.6/2 =) 648.6 < 660.3$]. With the adoption of blue-/green-/red-light color filter and polarizer at the receiving end, the polarized wavelengths are filtered and de-multiplexed in each polarized state due to modulation at different wavelengths.

For five wavelengths with parallel polarizations, signal-to-signal beating interference (SSBI) will worsen the performance of FSO-UWOC convergent systems on account of the natural feature of five wavelengths with parallel polarizations. However, the SSBI is trivially small due to large channel spacing among these five wavelengths. Furthermore, considering the orthogonal characteristic of *p*-polarized and *s*-polarized wavelengths, the cross-beating term will not exist [30]. Since that the SSBI is very small and the cross-beating term is almost zero, the color filter and polarizer can separate and recover the signals even if the five PAM4 inputs are not identical.

The optical transmittance with 0.3 (piped water) and 30.24 g/m^3 (turbid water) particle concentrations are presented in Fig. 3. Noticeably, low particle concentration brings on high optical transmittance [31]. In the state of 0.3 g/m^3 particle concentration (piped water), the optical transmittances in 450.6/488.2 nm blue and 520.4 nm green wavelengths are higher than the optical transmittances in 642.6 nm and 660.3 nm red ones, showing the practicality of piped water-based UWOC systems with blue- and green-light LDs. On the contrary, in the state of 30.24 g/m^3 particle concentration (turbid water), the optical transmittances in 642.6 nm and

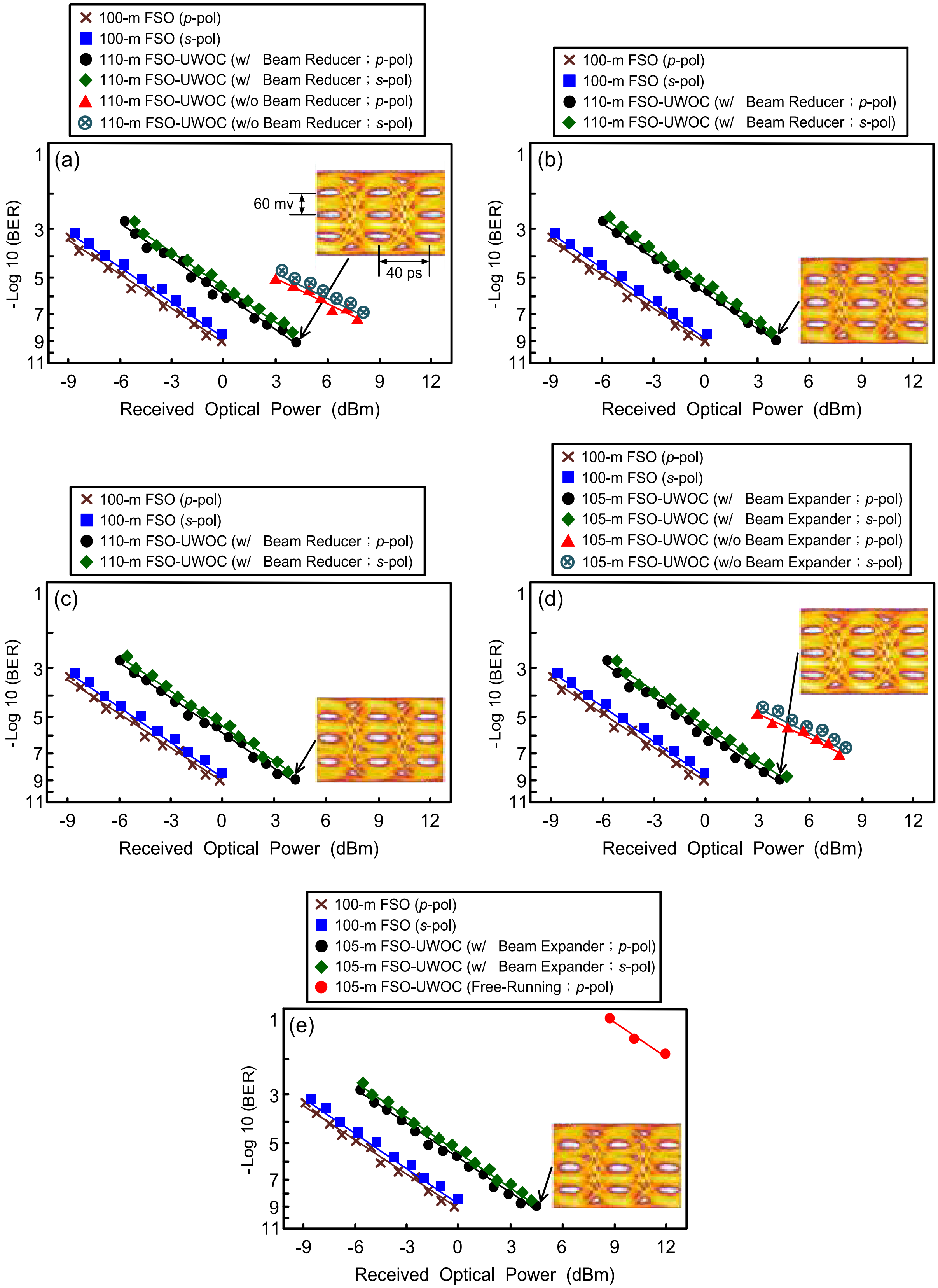

FIGURE 5. BER performances of 50 Gb/s PAM4 signal at a filtered wavelength of (a) 450.6 nm (b) 488.2 nm, (c) 520.4 nm, (d) 642.6 nm, and (e) 660.3 nm in the states over 100 m free-space transmission (*p*- and *s*-polarizations) and that over 100 m free-space transmission with either 10 m piped underwater link or 5 m turbid underwater link (*p*- and *s*-polarizations).

660.3 nm red-light wavelengths are higher than those in 450.6/488.2 nm blue and 520.4 nm green ones, showing the practicality of turbid water-based UWOC systems with red-light LD. Accordingly, blue- and green-light LDs are appropriate to a piped underwater channel, whereas red-light LD is appropriate to a turbid underwater channel.

Fig. 4 shows the S_{21} magnitude response of the equalizer. The aim of the equalizer is to enhance the magnitudes of high frequencies (16.5–26.25 GHz), compared to the magnitudes of low frequencies (DC–16.5 GHz), and bring on an increased signal-to-noise ratio and an enhanced BER.

Figs. 5(a), 5(b), 5(c), 5(d), and 5(e), respectively, show the BER performances of 50 Gb/s PAM4 signal at a filtered wavelength of 450.6 nm [Fig. 5(a)]/488.2 nm [Fig. 5(b)]/520.4 nm [Fig. 5(c)]/642.6 nm [Fig. 5(d)]/660.3 nm [Fig. 5(e)] in the states over 100 m free-space transmission (*p*- and *s*-polarizations) and that over 100 m free-space transmission with either 10 m piped underwater link or 5 m turbid underwater link (*p*- and *s*-polarizations). It is to be observed that the BER values of *p*- and *s*-polarizations are almost identical for five figures, revealing that the correlation between the BER performance and the polarization state is negligibly small. At a BER value of 10^{-9}, power penalties of 4.1 dB [Fig. 5(a)], 4.2 dB [Fig. 5(b)], and 4.4 dB [Fig. 5(c)] appear between the states over 100 m free-space transmission (*p*- or *s*-polarization) and that over 100 m free-space transmission with 10 m piped underwater link (*p*- or *s*-polarization). Given that absorption is the primary contributor in a piped underwater channel, these 4.1, 4.2, and 4.4 dB power penalties are mostly attributed to the absorption due to 10 m piped underwater link. And further, at a BER value of 10^{-9}, power penalties of 4.7 dB [Fig. 5(d)] and 4.8 dB [Fig. 5(e)] occur between the states over 100 m free-space transmission (*p*- or *s*-polarization) and that over 100 m free-space transmission with 5 m turbid underwater link (*p*- or *s*-polarization). Given that scattering is the main contributor in a turbid underwater channel, these 4.7 and 4.8 dB power penalties are chiefly ascribed to the scattering because of 5 m turbid underwater link. In addition, it is to be found that the power penalties of 4.7 and 4.8 dB [Figs. 5(d) and 5(e)] are somewhat higher than those of 4.1, 4.2, and 4.4 dB [Figs. 5(a), 5(b), and 5(c)]. Since that the optical transmittances of turbid water in red wavelengths are lower than those of piped water in blue and green wavelengths, shorter underwater link and higher received optical powers (higher power penalties) are required to make up for lower optical transmittances. As for PAM4 eye diagrams, eye diagrams with qualified attribute (*p*-polarization) are acquired in the status over 100 m free-space transmission and 10 m piped underwater link [Figs. 5(a), 5(b), and 5(c)]/5 m turbid underwater link [Figs. 5(d) and 5(e)]. Results show that, with a R/G/B five-wavelength polarization-multiplexing scheme, two blue-light LDs, one green-light LD, and two red-light LDs employing two-stage light injection and optoelectronic feedback techniques are satisfactorily enough to build a 500-Gb/s PAM4 FSO-UWOC convergence.

To have a more association with two-stage light injection and optoelectronic feedback techniques and BER performance, we measure the BER values of 50 Gb/s PAM4 signal in the free-running state [Fig. 5(e)]. Through 100 m free-space transmission and 5 m turbid underwater link (*p*-polarization), high BER values (poor BER performance) of $10^{-1} \sim 10^{-2}$ are acquired due to insufficient 3-dB bandwidth. This finding shows that a 500-Gb/s PAM4 FSO-UWOC convergence can't be implemented in the state of LDs with free-running. By contrast, as 50-Gb/s PAM4 signals are applied to the first step master LDs (LD1, LD4, LD7, LD10, and LD13), a 500-Gb/s PAM4 FSO-UWOC convergence can be realized in the state of LDs with two-stage light injection and optoelectronic feedback techniques, due to sufficient 3-dB bandwidth. Thereby, two-stage light injection and optoelectronic feedback techniques are needed in the setup so as to construct a 500-Gb/s PAM4 FSO-UWOC convergent system.

Moreover, to have a close connection with laser beam reducer/expander and BER performance, we take away the laser beam reducer/expander and compare the BER performances in the scenarios with and without a laser beam reducer/expander. Through 100 m free-space transmission and 10 m piped underwater link [Fig. 5(a)], BER achieves 3.8×10^{-7} without a laser beam reducer. However, BER gets better to 10^{-9} with a laser beam reducer. In piped underwater links, BER performance improves with a decrease in beam size. A smaller laser beam size that accompanies a lower absorption contributes more light to be received by the PD with a TIA receiver, bringing on better BER. Further, through 100 m free-space transmission and 5 m turbid underwater link [Fig. 5(d)], BER reaches 8.7×10^{-7} without a laser beam expander. Nevertheless, BER gets better to 10^{-9} with a laser beam expander. In turbid underwater links, BER performance improves with an increase in beam size. A larger beam size that follows a smaller beam divergence provides more scattered light to be received by the PD with a TIA receiver, bringing on better BER.

Over long-haul transmission at high transmission rate, polarization mode dispersion (PMD) becomes one of the restricting factors of FSO-UWOC convergent systems. A proper time delay between two polarization channels has a large impact on the PMD-induced crosstalk [32]–[34]. Nevertheless, since that the FSO-UWOC link is just 110 m/105 m, the PMD-induced crosstalk is restricted. Thus, a sophisticated time delay is not needed for such FSO-UWOC convergent system with a R/G/B five-wavelength polarization-multiplexing scheme.

IV. SUMMARY AND CONCLUSION

In this work with an innovative configuration on the FSO-UWOC convergent system, a polarization-multiplexing scheme is employed to transport the PAM4 data stream through the free-space transmission with either the piped underwater channel or the turbid underwater channel. The performances of 500 Gb/s PAM4 FSO-UWOC convergence utilizing R/G/B five-wavelength polarization-multiplexing scheme are investigated and discussed. Over 100 m free-space transmission with either 10 m piped underwater link or 5 m turbid underwater link, impressive BER performance and accepted PAM4 eye diagrams are attained with a total transmission rate of 500 Gb/s [50 Gb/s PAM4/wavelength × R/G/B five-wavelength × two orthogonal polarizations (*p*- and *s*-polarizations)]. Such established PAM4 FSO-UWOC convergent system meets the target of high-speed FSO-UWOC convergence given its workability for providing a high-transmission-rate over the free-space transmission with piped/turbid underwater link. It brings significant enhancements featured by optical wireless communications for affording high channel capacity with sufficient mobility.

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WEN-SHING TSAI received the M.S. and Ph.D. degrees from the Department of Electro-Optical Engineering, National Taipei University of Technology (NTUT), Taiwan, in 2003 and 2006, respectively. He joined the Department of Electrical Engineering, Ming Chi University of Technology, as an Assistant Professor, in 2006. He has promoted to an Associate Professor, in 2012. His research interests include FSO communications, FSO-UWOC convergence, and PAM4 modulation/transmission systems.

HAI-HAN LU (Senior Member, IEEE) received the M.S. and Ph.D. degrees from the Institute of Electro-Optical Engineering, National Central University, Taiwan, in 1991 and 2000, respectively.

He joined the Department of Electro-Optical Engineering, National Taipei University of Technology (NTUT), as an Associate Professor, in 2003. He has promoted to a Professor, a Distinguished Professor, and a Lifetime Distinguished Professor, in 2003, 2006, and 2017, respectively. He has authored or coauthored more than 200 articles in SCI cited international journals and more than 130 articles in international conferences. His research interests include FSO communications, UWOC transport systems, FSO-UWOC convergence, fiber-FSO convergence, and PAM4/PAM8 transmission systems. He is currently a Fellow of SPIE and IET and a Senior Member of OSA. He received the Sun Yat-Sen Academic Award (Natural Science), in 2017, the National Invention Award (Gold Medal), in 2016, the ICT Month Innovative Elite Products Award, in 2014 and 2016, the Outstanding Electrical Engineering Professor Award of The Chinese Institute of Engineering, in 2015, the Outstanding Engineering Professor Award of the Chinese Engineer Association, in 2013, and the Outstanding Research Award of NTUT, in 2004, for his significant technical contributions to FSO communications, UWOC systems, fiber-FSO convergence, and FSO-UWOC convergence.

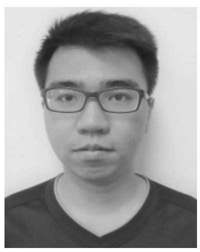
HSIAO-WEN WU received the M.S. and Ph.D. degrees from the Department of Electrical and Computer Engineering, Marquette University, USA, in 2000. In 2000, she joined the Department of Electronics Engineering, Tungnan University of Technology, Taipei, Taiwan, as an Assistant Professor. Her research interests include FSO communications, FSO-UWOC convergence, and speech quality in telecommunication.

SHI-CHENG TU was born in Taipei, Taiwan, in February 1995. He received the B.S. degree from the Ming Chi University of Technology (MCUT), New Taipei, Taiwan, in 2017. He is currently pursuing the M.S. degree with the Institute of Electro-Optical Engineering, National Taipei University of Technology (NTUT), Taiwan. His research interests focus on UWOC systems and FSO-UWOC convergence.

YONG-CHENG HUANG was born in Changhua, Taiwan, in December 1995. He received the B.S. degree from I-Shou University (ISU), Kaohsiung, Taiwan, in 2018. He is currently pursuing the M.S. degree with the Institute of Electro-Optical Engineering, National Taipei University of Technology (NTUT), Taiwan. His research interests focus on FSO communications and FSO-UWOC convergence.

JING-YAN XIE was born in Changhua, Taiwan, in September 1995. He received the B.S. degree from the National Yunlin University of Science and Technology, Yunlin, Taiwan, in 2018. He is currently pursuing the M.S. degree with the Institute of Electro-Optical Engineering, National Taipei University of Technology (NTUT), Taiwan. His research interests focus on PAM4 modulation/transmission systems and FSO-UWOC convergence.

QI-PING HUANG was born in Nantou, Taiwan, in August 1996. He received the B.S. degree from Feng Chia University, Taichung, Taiwan, in 2018. He is currently pursuing the M.S. degree with the Institute of Electro-Optical Engineering, National Taipei University of Technology (NTUT), Taiwan. His research interests focus on FSO communications and FSO-UWOC convergent systems.



SONG-EN TSAI was born in New Taipei, Taiwan, in December 1995. He received the B.S. degree from the National Yunlin University of Science and Technology (YunTech), Yunlin, Taiwan, in 2018. He is currently pursuing the M.S. degree with the Institute of Electro-Optical Engineering, National Taipei University of Technology (NTUT), Taiwan. His research interests focus on UWOC systems and FSO-UWOC convergence.