500-Gb/s PAM4 FSO-UWLT Integration Utilizing R/G/B Five-Wavelength Polarization-Multiplexing Scenario

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Abstract: A 500-Gb/s PAM4 FSO-UWLT integration utilizing red/green/blue polarization-multiplexing scenario is constructed. With five-wavelength polarization-multiplexing scenario, the transmission rate is substantially multiplied. Such demonstrated PAM4 FSO-UWLT integration brings imperative enhancement featured by optical wireless communications.

OCIS codes: (010.7340) Water; (060.2605) Free-space optical communication; (260.5430) Polarization.

1. Introduction

Free-space optical (FSO)-underwater wireless laser transmission (UWLT) integration is a promising one to overcome the connectivity problems [1-2]. It is an attractive integration that owns several advantages, such as license-free propagation, high directionality, no electromagnetic interference, and the reuse of atmospheric/underwater working bandwidths. With the fast development of FSO-UWLT integration, an increasing demand pushes the requirement for constructing a high-transmission-rate FSO-UWLT integration. In this work, a 500-Gb/s PAM4 FSO-UWLT integration through a 100-m free-space transmission with either a 10-m piped underwater link or a 5-m turbid underwater link is proposed, employing a red/green/blue (R/G/B) five-wavelength polarization-multiplexing scenario as a demonstration. Given that blue-light and green-light outperform red-light in piped underwater links, 450.6-nm blue-light, 488.2-nm blue-light, and 520.4-nm green-light laser diode (LD) transmitters with two-stage light injection and optoelectronic feedback techniques are adopted in a 110-m FSO-UWLT integration. Moreover, given that red-light outperforms blue-light and green-light in turbid underwater links, 642.6-nm and 660.3-nm red-light LD transmitters with two-stage light injection and optoelectronic feedback schemes are deployed in a 105-m FSO-UWLT integration. The aggregate transmission rate of FSO-UWLT integration is greatly increased twenty times by using PAM4 modulation with R/G/B five-wavelength polarization-multiplexing scenario [2 (PAM4 modulation) × 5 (five-wavelength) × 2 (polarization-multiplexing scenario) = 20]. To our knowledge, this demonstration is the first to effectively construct a R/G/B PAM4 FSO-UWLT integrated system with a total transmission rate of 500 Gb/s. With the adoption of doublet lenses in FSO communications and laser beam reducer/expander in UWLT links, brilliant bit error rate (BER) performance and qualified PAM4 eye diagrams are attained in this demonstrated FSO-UWLT integration.

2. Experimental Setup

The configuration of the illustrated 500 Gb/s PAM4 FSO-UWLT integration with a R/G/B five-wavelength polarization-multiplexing scenario over a 100-m free-space transmission with either a 10-m piped underwater link or a 5-m turbid underwater link is presented in Fig. 1. After amplification and linearization by a linear driver, a 50-Gb/s PAM4 signal with a pseudorandom binary sequence length of 2^{15}-1 is separated and fed into LD1, LD4, LD7, LD10, and LD13, respectively. 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. Subsequently, 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). The laser lights 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, recombined by a broadband polarization beam combiner, sent to a 100-m free-space link by a pair of doublet lenses, and split by a 1×2 optical splitter at the receiving site. For the upper/lower path, blue- (green-)/red-light color filter is utilized to select the wanted wavelength. After wavelength selection, the selected laser beam is supplied in a laser beam reducer/expander, delivered through a 10-m (2.5 m × 4) piped underwater link/5-m (2.5 m × 2) turbid underwater link, and inputted into a convex lens. Next, a polarizer is utilized to pick the desired *p*- or *s*-polarization. Then, the *p*-/*s*-polarized laser light is guided into fiber's ferrule and enhanced by a high-bandwidth photodiode (PD) with a trans-impedance amplifier (TIA) receiver. The enhanced 50 Gb/s PAM4 signal is then sent to an electrical equalizer for signal equalization, and launched into a 28-GHz error detector to measure the BER values. Further, a real-time oscilloscope is utilized to catch the eye diagrams of the transmitted 50 Gb/s PAM4 signal.

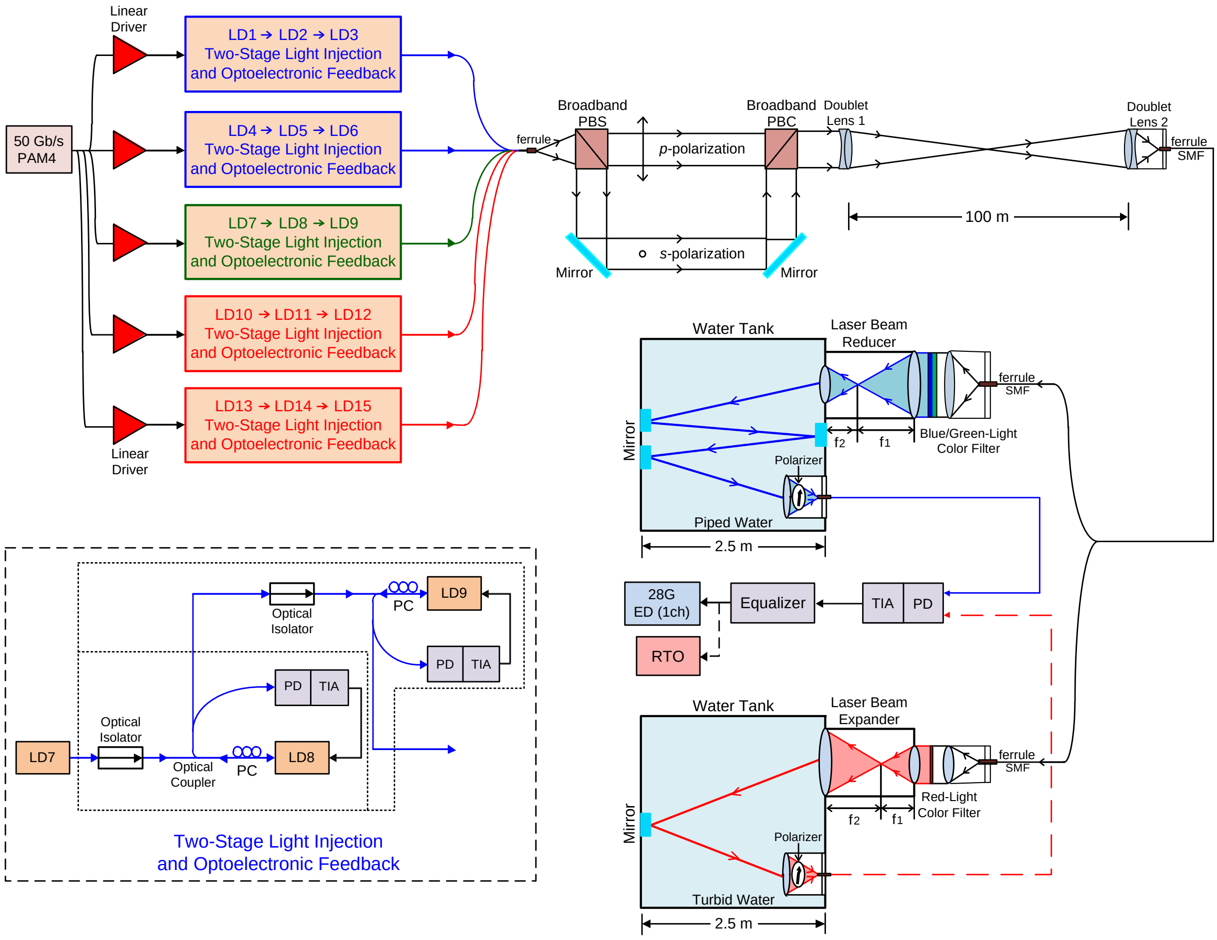

Fig. 1. The configuration of the illustrated 500 Gb/s PAM4 FSO-UWLT integration with a R/G/B five-wavelength polarization-multiplexing scenario over a 100-m free-space transmission with either 10-m piped underwater channel or 5-m turbid underwater channel.

3. Results and Discussions

Figs. 2(a), 2(b), 2(c), 2(d), and 2(e), respectively, present the BER performances of 50 Gb/s PAM4 signal at a selected wavelength of 450.6 nm [Fig. 2(a)]/488.2 nm [Fig. 2(b)]/520.4 nm [Fig. 2(c)]/642.6 nm [Fig. 2(d)]/660.3 nm [Fig. 2(e)] in the scenarios through a 100-m free-space transmission (*p*- and *s*-polarizations) and that through a 100-m free-space transmission with either a 10-m piped underwater link or a 5-m turbid underwater link (*p*- and *s*-polarizations). At a BER value of 10^{-9}, power penalties of 4.1 dB [Fig. 2(a)], 4.2 dB [Fig. 2(b)], and 4.4 dB [Fig. 2(c)] appear between the scenarios through a 100-m free-space transmission (*p*- or *s*-polarization) and that through a 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. Moreover, at a BER value of 10^{-9}, power penalties of 4.7 dB [Fig. 2(d)] and 4.8 dB [Fig. 2(e)] occur between the states through a 100-m free-space transmission (*p*- or *s*-polarization) and that through a 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. As for PAM4 eye diagrams, eye diagrams with qualified attribute (*p*-polarization) are acquired in the status over a 100-m free-space transmission with 10-m piped underwater link [Figs. 2(a), 2(b), and 2(c)]/5-m turbid underwater link [Figs. 2(d) and 2(e)]. And further, we take away the laser beam reducer/expander and compare the BER performances in the status with and without a laser beam reducer/expander. Through a 100-m free-space transmission with 10-m piped underwater link [Fig. 2(a)], BER achieves a value of 3.8×10^{-7} without a laser beam reducer. However, BER gets better to 10^{-9} with a laser beam reducer. 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. Additionally, through a 100-m free-space transmission with 5-m turbid underwater link [Fig. 2(d)], BER reaches 8.7×10^{-7} without a laser beam expander.

Nevertheless, BER gets better to 10^{-9} with a laser beam expander. A larger beam size that follows a smaller beam divergence provides more scattered light to be received by the PD with a TIA receiver, resulting in better BER.

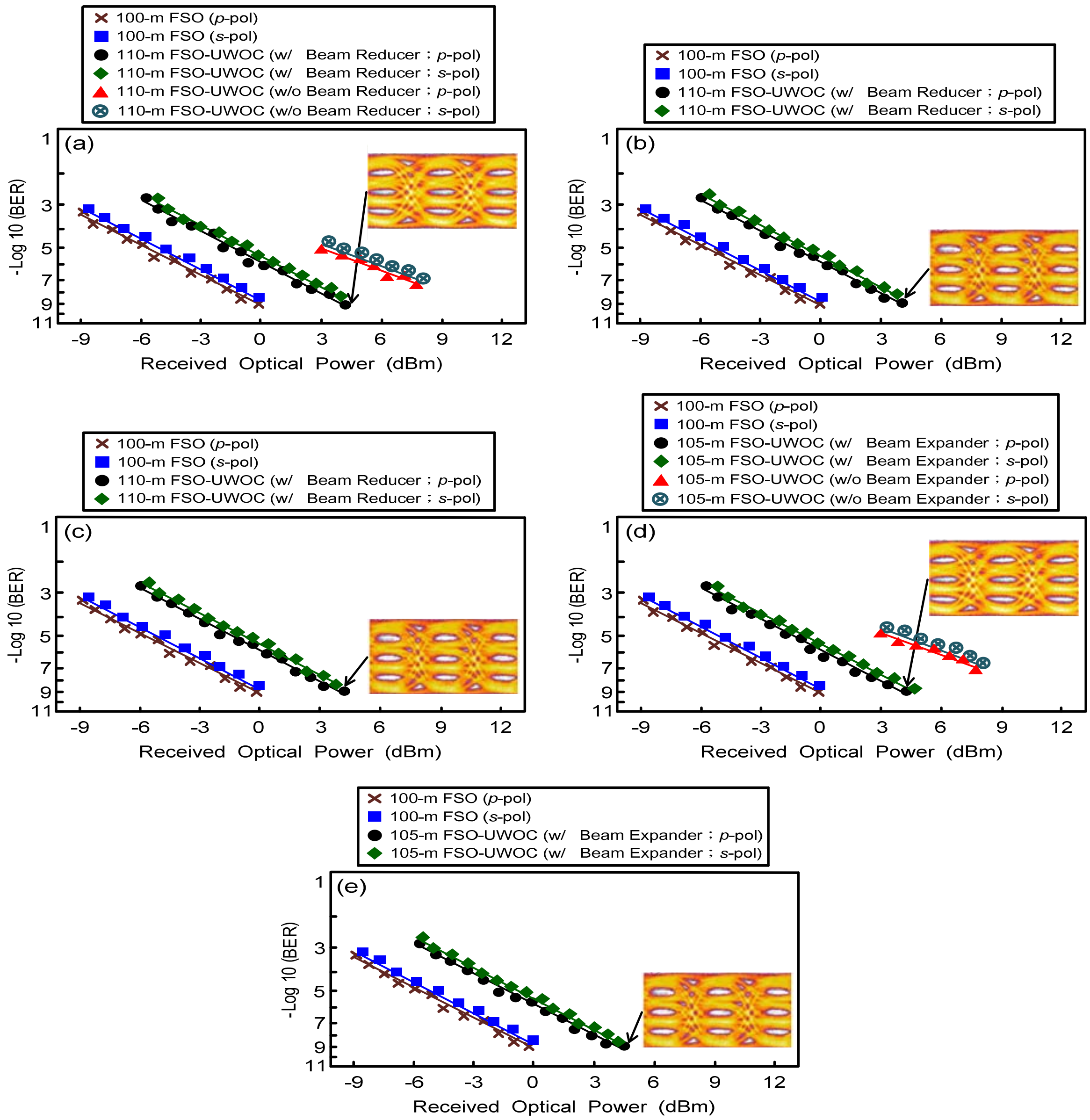

Fig. 2. The BER performances of 50 Gb/s PAM4 signal at a selected wavelength of **(a)** 450.6 nm **(b)** 488.2 nm, **(c)** 520.4 nm, **(d)** 642.6 nm, and **(e)** 660.3 nm in the scenarios through a 100-m free-space transmission (*p*- and *s*-polarizations) and that through a 100-m free-space transmission with either 10-m piped underwater link or 5-m turbid underwater link (*p*- and *s*-polarizations).

4. Conclusion

In this demonstration with an innovative configuration on the FSO-UWLT integration, a polarization-multiplexing scenario is deployed to transport the PAM4 data stream through the free-space transmission with either the piped underwater link or the turbid underwater link. The performances of 500 Gb/s PAM4 FSO-UWLT integration utilizing R/G/B five-wavelength polarization-multiplexing scenario are investigated and discussed. Over a 100-m free-space transmission with either 10-m piped underwater link or 5-m turbid underwater link, excellent BER performance and qualified PAM4 eye diagrams are attained with an aggregate transmission rate of 500 Gb/s.

5. References

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