52 m /9 Gb/s PAM4 plastic optical fiber-underwater wireless laser transmission convergence with a laser beam reducer

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A 52 m/9 Gb/s four-level pulse amplitude modulation (PAM4) plastic optical fiber (POF)-underwater wireless laser transmission (UWLT) convergence with a laser beam reducer is proposed. A 52 m/9 Gb/s PAM4 POF-UWLT convergence is practically demonstrated with the application of a laser beam reducer to reduce the collimated beam diameter. A 50 m graded-index (GI)-POF is employed as an underwater extender to efficiently enhance the coverage of UWLT. The performances of PAM4 POF-UWLT convergence in view of bit error rate (BER) and eye diagrams improve with the decrease of the collimated beam diameter because of the small amount of light absorbed by clear ocean water. Competent BER and eye diagrams (three independent eye diagrams) are achieved over a 50 m GI-POF transmission with a 2 m clear ocean water link.

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Underwater wireless laser transmission (UWLT), a promising provider of high-speed underwater links, has obtained considerable interest over the past few years. Some recent works have shown that high-speed UWLTs can be achieved over finite underwater links[1,2]. Transmissions of several gigabit per second (Gb/s) with limited underwater links have been implemented using different water types with attenuation characteristics, which is a combination of absorption and scattering. Nevertheless, transmissions of several Gb/s with long-reach underwater links have not been realized. For the real implementation of high-speed UWLTs, constructing a long-reach underwater link is a major concern of system designers[3,4]. Many applications of UWLTs have been proposed for environmental monitoring, disaster precaution, offshore exploration, and underwater oil pipe investigation. To meet the demands of different applications, a high-speed UWLT with a long-reach underwater link is required. A new transmission medium different from the aquatic medium is required to realize a long-reach underwater link. A graded-index (GI) plastic optical fiber (POF) has been developed with good features, such as large core diameter, small bending radius, high bandwidth-distance product, and low transmission loss[5,6]. The GI-POF can enhance the coverage of UWLT and, thus, can be effectively utilized as an underwater extender of UWLT. As a result, a long-reach underwater link can be practicably constructed by adopting a POF-UWLT convergence[7]. In this Letter, a 9 Gb/s four-level pulse amplitude modulation (PAM4) POF-UWLT convergence with a laser beam reducer for reducing the collimated beam diameter over a 50 m GI-POF transmission with a 2 m clear ocean water link is proposed. For the first time, to the authors' knowledge, a 52 m/9 Gb/s PAM4 POF-UWLT convergence is practically demonstrated with the application of a laser beam reducer to reduce the collimated beam diameter. For reducing the collimated beam diameter, the laser beam reducer converts a large collimated beam diameter into a small one. The laser beam reducer has been adopted in free-space optical (FSO) communications to improve the performances of FSO links[8]. However, it has not been adopted as the performance improvement scheme in POF-UWLT convergence. POF-UWLT convergence presents several similarities compared to FSO links due to the fact that they utilize optical wavelengths to deliver data signals between dedicated point-to-point links. A laser beam reducer, which can reduce the collimated beam diameter, is thereby expected to improve the performances of PAM4 POF-UWLT convergence. The performances of PAM4 POF-UWLT convergence in view of bit error rate (BER) and eye diagrams improve with the decrease of the collimated beam diameter[9] because of the lower amounts of light absorbed by clear ocean water. Competent BER and clear eye diagrams (three independent eye diagrams) are acquired at a 50 m GI-POF operation with a 2 m clear ocean water link. Our novel proposal reveals a more prominent one than those of UWLTs with short-reach and low-speed characteristics. This proposed 52 m/9 Gb/s PAM4 POF-UWLT convergence is demonstrated to be superior over the prior UWLTs, given its feasibility for long-reach and high-speed underwater links.

The configuration of the proposed 52 m/9 Gb/s PAM4 POF-UWLT convergence with a laser beam reducer to reduce the collimated beam diameter is presented in Fig. 1. A two-channel pseudorandom bit sequence (PRBS)

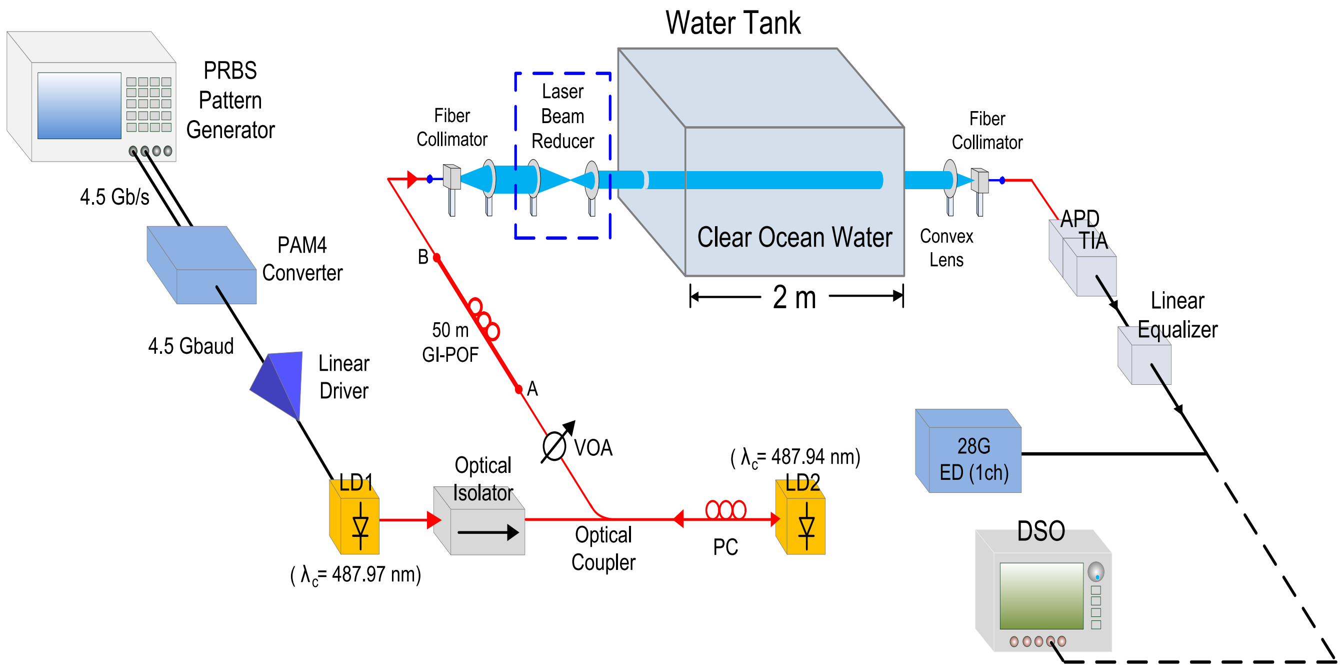

Fig. 1. Configuration of the proposed 52 m/9 Gb/s PAM4 POF-UWLT convergence with a laser beam reducer to reduce the collimated beam diameter.

pattern generator (Anritsu MP1800 A) produces two binary PRBS data streams at 4.5 Gb/s with a length of 2^{15}–1. The amplitudes of these two binary data streams are 1 and 0.5 V. A PAM4 converter (Anritsu G0375 A) is utilized to convert two 4.5 Gb/s non-return-to-zero (NRZ) signals into a 9 Gb/s PAM4 signal. After electrical amplification by a linear driver (Tektronix PSPL5866), the 9 Gb/s PAM4 signal is sent to laser diode 1 (LD1, Thorlabs LP488-SF20) with a central wavelength of 487.97 nm. LD2 (slave laser) with a central wavelength of 487.94 nm is injection-locked by LD1 (master laser) via a combination of an optical isolator (Global E-Photonics) and an optical coupler (Thorlabs TW470R5A2). Both LDs are mounted by LD/thermoelectric cooler (TEC) mounts (Thorlabs LDM9LP). Given an operation current of 70 mA, a maximum optical output power of 20 mW is obtained for LD1 and LD2. Since blue light around the 488 nm is close to the minimum of absorption in water, and 488 nm LDs are available at our laboratory, 488 nm blue light LDs with high optical output powers are adopted in a POF-UWLT convergence. In this experiment, LD1 (master) is modulated. If instead of the master LD2 (slave) is modulated with the PAM4 signal, there should be a less attenuation of the data[10]. However, the attenuation of the data can be compensated by the electrical amplification of the linear driver. The performances of POF-UWLT convergence affected by low modulation suppression values are limited. The light emitted from the injection-locked LD2 is inputted into a variable optical attenuator (VOA) and then sent to a 50 m GI-POF (Comoss GI-POF cable). A VOA is introduced at the start of the 50 m GI-POF to adjust the optical power level. This 50 m GI-POF possesses a 3 dB bandwidth of 2.8 GHz, a core diameter of 1 mm, and a total power loss of around 7 dB [transmission loss and power connection loss due to different core sizes between the single-mode fiber and the GI-POF (points A and B)]. The light sent out from the fiber collimator (μLS FL10-VIS1-40) at the transmitting site is coupled to a convex lens with 50 mm focal length to form a parallel optical beam and launched into a laser beam reducer to reduce the collimated beam diameter. Then, it is transmitted in the clear ocean water, coupled to a convex lens with 25.4 mm focal length, and concentrated on the fiber collimator at the receiving site. The 2 m long water tank is filled with clear ocean water (attenuation coefficient $= 0.151\ \mathrm{m}^{-1}$). Many applications of UWLTs have been proposed for underwater oil pipe observation, environmental monitoring, and disaster prevention. To meet the demands of applications of UWLTs, thereby, clear ocean water is utilized in this work. Over a 2 m clear ocean water link, the laser light is received by a 10 GHz avalanche photodiode (APD) with a trans-impedance amplifier (TIA) receiver (DSC-R402APD). After electrical equalization by a linear equalizer (MAX 3986), the performances of the proposed 9 Gb/s PAM4 POF-UWLT convergence are evaluated in real-time by BER and eye diagrams. The BER value is measured via auto-search using a 28 Gb/s error detector (ED) and the PAM4 three-eye sampling method[10]. Using this PAM4 BER measurement to calculate the total BER entails a low cost. Furthermore, a digital storage oscilloscope (DSO) is utilized to capture the eye diagrams of the delivered 9 Gb/s PAM4 signal.

The laser beam reducer for reducing the collimated beam diameter is illustrated in Fig. 2. It comprises two

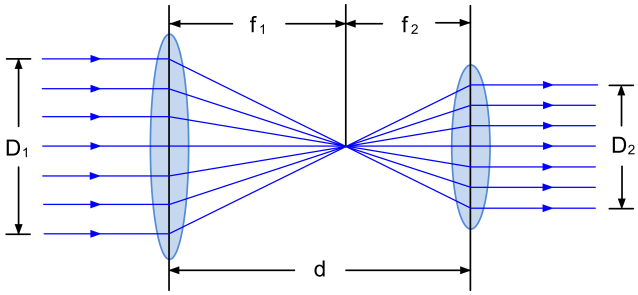

Fig. 2. Laser beam reducer for reducing the collimated beam diameter.

convex lenses with dissimilar focal lengths of f_1 and f_2 ($f_1 > f_2$). The sum of the focal lengths ($f_1 + f_2$) is equal to the separation distance of two convex lenses (d). A large collimated beam diameter (D_1) is converted into a small one (D_2) by employing a laser beam reducer. Two convex lenses with 50 mm (f_1) and 25.4 mm (f_2) focal lengths are adopted. The laser beam reducer converts a 4.4 mm large collimated beam diameter (D_1) into a 2.2 mm small one (D_2). Furthermore, we change two convex lenses with different focal lengths to further reduce the collimated beam diameter. Two convex lenses with 60 mm (f_1) and 15.29 mm (f_2) focal lengths are adopted. Under this scenario, the laser beam reducer transforms a 4.4 mm large collimated beam diameter (D_1) into a 1.1 mm small one (D_2).

For GI-POF, the amount of modal dispersion is given by[11]

$$D_{\text{dispersion}} = \mathrm{NA}^2 \times \frac{L}{2n(r)v_g}, \tag{1}$$

where NA is the numerical aperture, L is the length of GI-POF, $n(r)$ is the refractive index profile of GI-POF, and v_g is the group velocity. According to Eq. (1), a longer GI-POF length generates a larger modal dispersion, thereby resulting in worse transmission performance. Nevertheless, since the GI-POF is only 50 m long, the performance decline because of the modal dispersion is limited. Moreover, given that the GI-POF transmission length is 50 m, the bandwidth-distance product is 140 MHz $\cdot$ km (2.8 GHz $\times$ 0.05 km), which satisfies the bandwidth-distance product requirement of GI-POF (<150 MHz $\cdot$ km)[12]. It indicates that the performance degradation caused by a 50 m GI-POF is restricted. As the length of the GI-POF is 53.6 m, the bandwidth-distance product is around 150 MHz $\cdot$ km (2.8 GHz $\times$ 0.0536 km). It exactly meets the bandwidth-distance product demand of the GI-POF. Consequently, as the length of the GI-POF is longer than 53.6 m, the BER performance degradation caused by modal dispersion due to the GI-POF is intolerable. Furthermore, the maximum transmission rate (T_{MAX}) is given by

$$T_{\text{MAX}} \leq \frac{2v_g}{n(r)L\Delta^2}, \tag{2}$$

where Δ is the relative index between core and cladding. A shorter GI-POF length generates a larger value on the right side of Eq. (2), thereby leading to a higher transmission rate and also a higher 3 dB bandwidth (the bandwidth is 0.7 times the transmission rate[13]). Given that a 50 m GI-POF owns a 3 dB bandwidth of 2.8 GHz, by adopting PAM4 modulation[14], the maximize transmission rate can reach 7.92 Gb/s ($2.8 \times \sqrt{2} \times 2 = 7.92$).

Figure 3 shows the S_{21} characteristic of the linear equalizer. Clearly, the magnitudes of high frequencies (1.5–5.5 GHz) are higher than those of low frequencies (DC–1.5 GHz). Linear equalization refers to an enhancement scheme to enhance the magnitudes of high frequencies in comparison with those magnitudes of low frequencies[15]. The function of the linear equalizer is to render the frequency response and improve the performances of the proposed 9 Gb/s PAM4 POF-UWLT convergence.

Figure 4 presents the frequency responses of the PAM4 POF-UWLT convergence under the conditions of free-running over a 2-m clear ocean water link, injection locking over a 2 m clear ocean water link, injection locking over a 50 m GI-POF transport with a 2 m clear ocean water link, and injection locking over a 50 m GI-POF transport with a 2 m clear ocean water link but without a linear equalizer at the receiving site, respectively. Under the condition of free-running, a 3 dB bandwidth of 1.7 GHz is obtained over a 2 m clear ocean water link. Under the condition of LD2 with injection locking, a 3 dB bandwidth of 3.6 GHz is obtained over a 2 m clear ocean water link. This 3 dB bandwidth enhancement (1.7 GHz → 3.6 GHz) is attributed to the effect of injection locking. Moreover, the frequency response is characterized by a high-frequency resonance peak and a drop in the middle frequencies to obtain a significant 3 dB bandwidth enhancement[16]. Under the condition of LD2 with injection locking, a 3 dB bandwidth of 3.2 GHz is acquired at a 50 m GI-POF operation with a 2 m clear ocean water link. This bandwidth reduction (3.6 GHz → 3.2 GHz) results from the bandwidth

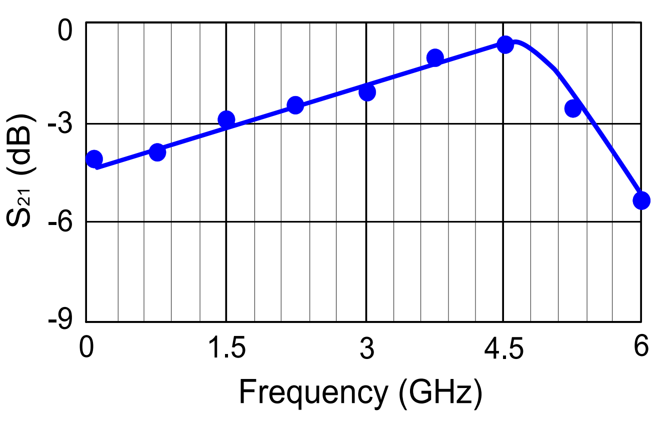

Fig. 3. S_{21} characteristic of the linear equalizer.

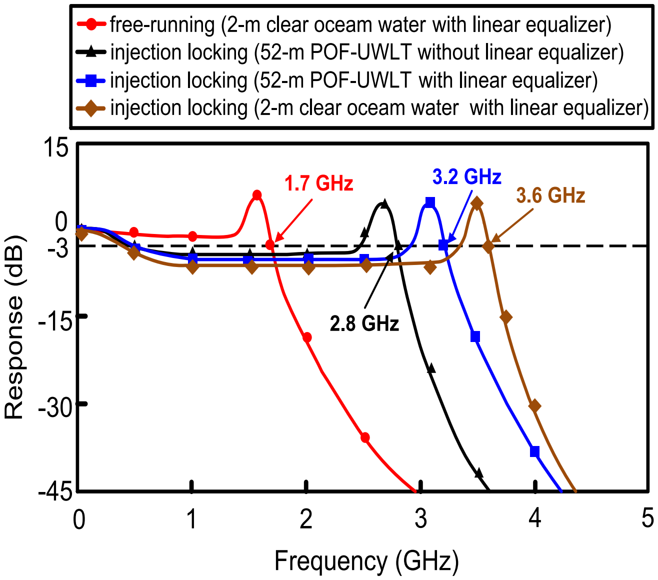

Fig. 4. Frequency responses of the PAM4 POF-UWLT convergence under different conditions.

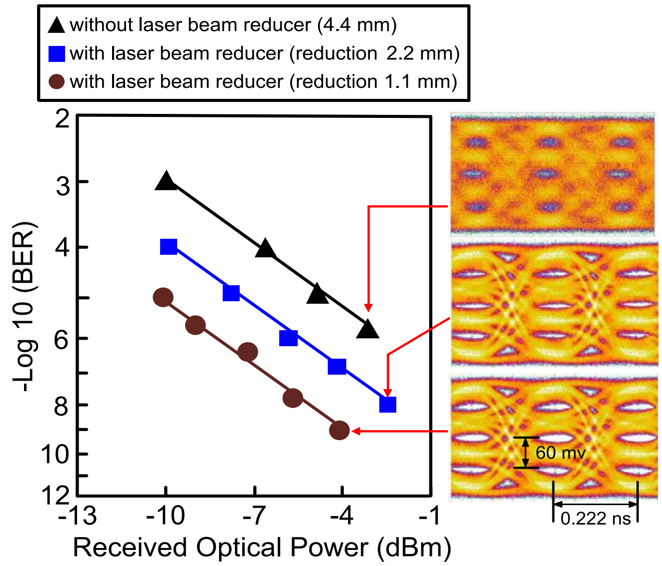

Fig. 5. BER performances of the 52 m/9 Gb/s PAM4 POF-UWOT convergence at a 50 m GI-POF operation with a 2 m clear ocean water link.

limitation of the 50 m GI-POF. As the transmission rate is $\sqrt{2}$ times the bandwidth[13], a 9 Gb/s PAM4 POF-UWLT convergence ($3.2 \times \sqrt{2} \times 2 = 9.05 > 9$) can be sufficiently realized at a 50 m GI-POF operation with a 2 m clear ocean water link. Furthermore, in order to verify the relation between frequency response and linear equalizer, we remove the linear equalizer and measure the frequency response of the PAM4 POF-UWLT convergence. Clearly, the 3 dB bandwidth reduction due to linear equalizer is 0.4 GHz (3.2 GHz → 2.8 GHz).

The BER performances of the 52 m/9 Gb/s PAM4 POF-UWOT convergence at a 50 m GI-POF operation with a 2 m clear ocean water link are shown in Fig. 5. Without a laser beam reducer (with a diameter of 4.4 mm), the BER value deteriorates to 1×10^{-6}. With a laser beam reducer for reducing the collimated beam diameter (with a diameter of 2.2 mm), the BER value reaches 1×10^{-8}. This BER performance improvement ($10^{-7} \to 10^{-8}$) mainly results from the reduction of the collimated beam diameter (4.4 mm → 2.2 mm). To have more of a connection with the laser beam reducer for reducing the collimated beam diameter and BER performance, we further reduce the collimated beam diameter and measure the BER value. With a laser beam reducer for further reducing the collimated beam diameter (with a diameter of 1.1 mm), the BER value improves to 1×10^{-9}. The further improvement of the BER performance ($10^{-8} \to 10^{-9}$) is chiefly attributed to the further reduction of the collimated beam diameter (2.2 mm → 1.1 mm). In the underwater channel, the overall attenuation coefficient $c(\lambda)$ can be stated as

$$c(\lambda) = a(\lambda) + s(\lambda), \tag{3}$$

where $a(\lambda)$ and $s(\lambda)$ are coefficients of water associated with absorption and scattering. In clear ocean water, the coefficients of $a(\lambda)$, $s(\lambda)$, and $c(\lambda)$ are 0.114 (m^{-1}), 0.037 (m^{-1}), and 0.151 (m^{-1}) ($0.114 + 0.037 = 0.151$), respectively[17]. Given that $a(\lambda)$ offers approximately three times the value of $s(\lambda)$ (0.037 × 3–0.114), absorption is the primary limiting factor in clear ocean water. With the application of the laser beam reducer for reducing the collimated beam diameter (4.4 mm → 2.2 mm), the performances of PAM4 POF-UWOT convergence are improved due to lower amounts of light absorbed by clear ocean water (higher amounts of light received by an APD with a TIA receiver). A smaller collimated beam diameter leads to lower absorption and higher optical signal-to-noise ratio (OSNR), thereby resulting in a lower BER. Moreover, with the application of the laser beam reducer for further reducing the collimated beam diameter (2.2 mm → 1.1 mm), the performance of PAM4 POF-UWOT convergence is further improved due to even lower amounts of light absorbed by clear ocean water (even higher amounts of light received by an APD with a TIA receiver). An even smaller collimated beam diameter leads to even lower absorption and even higher OSNR, thereby leading to an even lower BER. In addition, at the same received optical power, the optical power of the injection-locked LD2 transmitter for the scenario with a diameter of 4.4 mm is higher than that of the scenario with a diameter of 1.1 mm (by adjusting the optical power of the injection-locked LD2 transmitter), thereby resulting in lower OSNR and higher BER. At a received optical power of −4 dBm, the collimated beam diameter by which 1×10^{-9} BER operation can be obtained is 1.1 mm. With a collimated beam diameter of 2.2 mm, the received optical power is −2.3 dBm to compensate for the OSNR decrement. However, the compensation is limited by which just 1×10^{-8} BER operation is acquired. The eye diagrams of the 9 Gb/s PAM4 signal with/without a laser beam reducer for reducing the collimated beam diameter are also shown in Fig. 5. For the scenario without a laser beam reducer, excessive amplitude and phase fluctuations are observed in eye diagrams. For the scenario with a laser beam reducer to reduce the collimated beam diameter to 2.2 mm, somewhat clear eye diagrams exist. For the scenario with a laser beam reducer to further reducing the collimated beam diameter to 1.1 mm, clear eye diagrams exist. As the collimated beam diameter with a narrow beam occurs, POF-UWOT convergence presents competent overall performances in terms of BER (1×10^{-9}) and eye diagrams (clear eye diagrams) because of the lower amounts of light absorbed by clear ocean water.

In conclusion, a long-reach and high-speed 52 m/9 Gb/s PAM4 POF-UWLT convergence with a laser beam reducer for reducing the collimated beam diameter is proposed and practically demonstrated. A 50 m GI-POF is adopted as an underwater extender to effectively enhance the coverage of UWLT. A laser beam reducer is employed as a performance improvement scheme to improve the overall performances. At a 50 m GI-POF operation with a 2 m clear ocean water link, the performances of the proposed 9 Gb/s PAM4 POF-UWLT convergence are evaluated by BER and eye diagrams in real-time. Competent BER and clear eye diagrams are acquired over a 50 m GI-POF transport with a 2 m clear ocean water link. This innovative 52 m/9 Gb/s PAM4 POF-UWLT convergence provides the characteristics of long-reach and high-speed underwater links, which can accelerate the deployment of POF-UWLT convergence.

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