Super Wide-Flat Beam Transmission over Scatter-prone Underwater Channel Using Twin Parallel Flat-Narrow Beams Generated by Aspheric Lens Pair-type Beam Shaper

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Abstract: Our experiments demonstrate that the use of a twin flat-narrow beam system with time-domain hybrid PAM signals in underwater channels of up to 4 m significantly improves the elastic transmission capacity from 625-Mbps to 1.25-Gbps.
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1. Introduction

In the context of next-generation mobile communication standards, such as Beyond 5G/6G, there is a growing demand for gigabit-level, low-latency, and high-capacity communication connections in various environments, including non-terrestrial networks. In addition to radio-frequency wireless communication, optical wireless communication has been reported as a promising method [1-3]. Light beam output from laser diodes (LDs) has the potential for low latency, low loss, and high capacity in underwater channels, making them suitable for underwater optical wireless communication systems [4]. In relatively turbid underwater environments, such as underwater channels, blue to green light exhibits excellent transmission characteristics within the visible light spectrum [5].

Beam-shaping methods employing high-scattering-resistant Laguerre-Gaussian [6], radially symmetric cubic phase profiles, or Fresnel lens shapes [7] have been proposed as approaches for beam-shaping in scattering media. Flat-narrow beams generated by Galilean telescope-type beam shapers can transform a typical Gaussian beam into a flat-topped beam with low loss, allowing transmission with suppressed beam spreading [8]. Time-domain hybrid pulse amplitude modulation (TDHP) consisting of two-level pulse amplitude modulation (PAM2) and four-level pulse amplitude modulation (PAM4) was proposed to maximize the transmission capacity of the transmission distance in underwater channels [9]. However, achieving both beam shaping and high-capacity transmission with a single beam is limited because of the entropy-energy relationship. Expanding from single-beam to multi-beam transmission allows for beam shaping and increased capacity. Employing diversity reception alongside multi-beam transmission makes it possible to improve the receiver sensitivity and extend the transmission distance. In the case of multiple Gaussian beams [10], the increase in transceiver size can be mitigated by separating the laser placements and widening the beam spacing to reduce the effects of beam interference.

In this study, we experimentally verified the underwater channel transmission using twin-parallel flat narrow beams in the visible light spectrum. We evaluated the beam-to-beam crosstalk resistance of TDHP signals for parallel twin flat narrow beams and compared them with Gaussian-shaped parallel twin beams. The advantage of narrow beam spreading in flat beams is that it allows for close beam spacing, enabling the miniaturization of transceivers. This report represents the first investigation into the application of narrow flat beams in underwater channels, rather than flat envelope beam groups composed of multiple Gaussian beams.

2. Principle of generation and propagation of parallel twin beam

The generalized optical configuration for generating closely spaced parallel twin beams is shown in Fig. 1. Figures

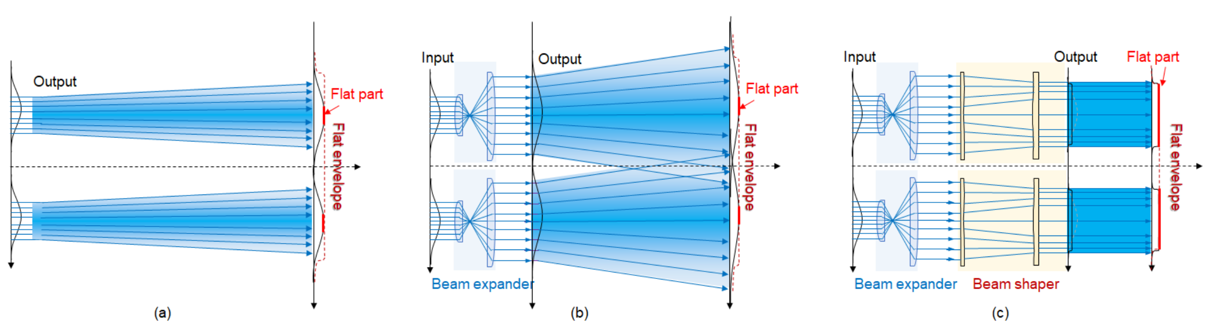

Fig. 1. Generation and propagation of twin beams, (a) uncoupled partial flat, (b) coupled partial flat, and (c) uncoupled super wide-flat.

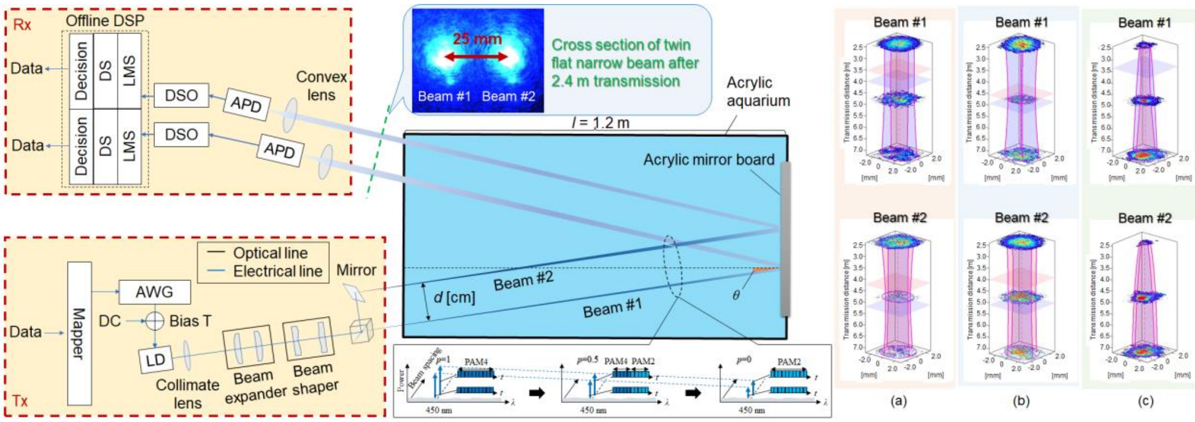

Fig. 2. Experimental setup and twin beam profiles (a) uncoupled partial flat, (b) coupled partial flat, and (c) uncoupled super wide-flat.

1(a) and 1(b) illustrate the propagation of twin beams composed of collimated and beam-expanded Gaussian beams. During propagation, beam crosstalk occurs because the beams spread out from their beam waists after the laser output, leading to signal quality degradation. Figure 1(c) illustrates the propagation of twin-parallel flat narrow beams generated by parallel Galilean beam shapers. Adjusting the position of the rear-stage aspheric lenses within each Galilean beam shaper results in a change in the intensity distribution of the input Gaussian beam at the output stage. Narrow flat-top beams were generated at the output by optimizing the distance between two aspheric lenses. There are two methods to load data for twin beams: using the same or different data for each beam. A beam consisting of multiple flat beams with flat beam intensity over a wide range is defined as a super-wide flat beam.

3. Experimental setup

Figure 2 illustrates the experimental setup for the underwater channel transmission of twin beams. On the transmitter side, the data bit sequence was converted into two types of TDHP signals, PAM2 and PAM4, by using a mapper. The TDHP signals used in this study had three patterns for the *p* parameter, corresponding to 0, 0.5, and 1, representing the proportion of PAM4 modulation signals to the overall symbols.

The symbol sequence of the TDHP signal was output as an electrical signal through an arbitrary waveform generator (AWG) with a direct current (DC) component added by bias T. The TDHP signal was directly modulated by an LD with a center wavelength of 450 nm and focused using a focusing lens. The Gaussian-shaped collimated light was shaped into the desired beam profile using a beam expander and shaper. Three different beam profiles–a collimated Gaussian beam, an expanded Gaussian beam, and a flat-top beam–were used for comparison. Each beam was split into a main beam on the transmission side and a side beam on the refractive side using a beam splitter. The side beam was adjusted to be parallel to the main beam using mirrors, and the twin-beam spacing was adjusted by changing the mirror position. The transmitted powers of each beam for the collimated Gaussian beam, beam-expanded Gaussian beam, and flat-top beam are 2.7 dBm, 1.9 dBm, and 1.1 dBm, respectively. The insertion losses of the beam expander and beam shaper were 0.8 dB. The two beams × 312.5 Msymbol/s/beam TDHP signals are propagated through an acrylic water tank filled with tap water, measuring 0.45 m × 1.2 m × 0.6 m × 0.01 m (height × length × width × thickness). The acrylic mirrors reflect them and travel back and forth within the water tank before being transmitted underwater to air. The transmission distance was adjusted by varying the number of reflections from the acrylic mirror. Images obtained with a camera present the cross-section of twin flat beams after 2.4 m of underwater channel transmission. It can be confirmed that the two closely spaced beams maintain a nearly constant intensity within the beam.

On the receiver side, each beam was focused by a condenser lens and converted into electrical signals using an avalanche photodiode (APD). Electrical signals from each APD output were converted into digital signals using a digital storage oscilloscope. In the offline digital signal processing unit, the sampled signals are time-domain equalized using the least mean squares (LMS) algorithm, downsampled, and subjected to decision processing. The LMS algorithm was applied to a 15-tap finite-impulse response filter. Following decision processing, the restored data bit sequence calculates the bit error ratio (BER). For a single beam, the side beam was terminated by shading to measure the BER. For the twin beams, the quality of the two received signals was used to calculate the average error rate of the beams. In this experiment, a Reed-Solomon error correction code with a redundancy of 7 % was assumed, and the forward error correction (FEC) limit was set to BER = 3.8×10^{-3}.

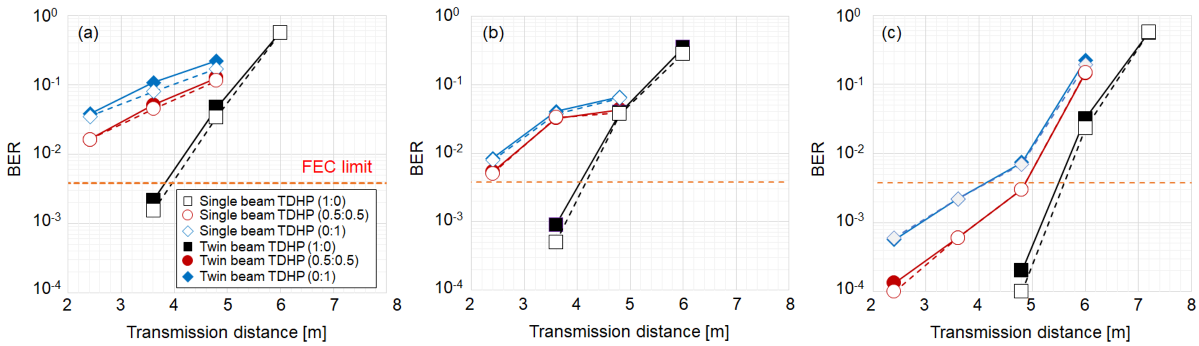

Fig. 3. Experimental BERs for transmission distance (a) uncoupled partial flat, (b) coupled partial flat, (c) uncoupled super wide-flat.

4. Experimental results

Figure 2(a-c) compares beam profiles for transmission distances up to 7 m. In the case of the twin flat beams, we observed that both beams maintained high-intensity power at the beam center. The twin beams of the collimated and beam-expanded Gaussian beams indicate that the beam width is comprehensive from the initial transmission stage. As the distance increased, the beams gradually spread.

Figure 3 compares the BER characteristics of the three types of TDHP signals for transmission distances up to 7 m. By decreasing the *p* parameter of the TDHP signals, the available transmission length at which the FEC limit can be reached can be increased. For twin flat beams, the transmission distances at FEC limit for TDHP (1:0), TDHP (0.5:0.5), and TDHP (0:1) are 4.2 m, 4.9 m, and 5.5 m, respectively, with minimal penalty compared to single flat beams. Twin beams consisting of collimated Gaussian and beam-expanded Gaussian beams only reach the FEC limit at TDHP (0:1), with respective transmission distances of 3.8 m and 4.1 m. The impact of noise degradation was more significant than the effect of beam interference owing to beam spreading, indicating that beam interference did not affect the signal quality. Therefore, we confirmed that twin-flat beams, which enable long-distance transmission without beam interference, can significantly alter the maximum transmission capacity through adaptive modulation with twin beams.

5. Conclusions

We experimentally demonstrated super-wide-flat beam transmission over an underwater channel using time-domain adaptive modulation signals employing twin flat-narrow beams of the same wavelength. Our experiments successfully demonstrated significant variability in the transmission capacity within a single wavelength. This achievement is attributed to the spatial multiplexing enabled by the flat-narrow beams, mitigating inter-beam interference, and contributing to the miniaturization of the transceiver sizes.

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