Broadband Single Flat Narrow Beam Shaped Time-domain Adaptive Modulation for Underwater Transmission with Wavelength Characteristics in Blue-green WDM System

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Abstract: We experimentally demonstrated that time-domain adaptive modulation per wavelength optimizes the underwater transmission capacity of a broad-spectrum WDM-TDHP comprising 450 nm and 520 nm wavelengths, shaped into a flat-narrow beam using a Galileoscope-type beam shaper.
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1. Introduction

Optical wireless communication has garnered attention owing to its superiority over radio-frequency communication in specialized environments, such as space, underwater, and indoor settings [1-3]. A time-domain hybrid pulse amplitude modulation (TDHP) signal that optimizes the mixture ratio of two-level pulse amplitude modulation (PAM2) and four-level PAM (PAM4) signals in the time domain can maximize the transmission capacity per wavelength for a particular transmission distance [4]. In optical communications with strong directionality and straight-line propagation, it is possible to achieve enhanced reception power efficiency, longer distances, and higher capacity by spatially transmitting energy densely towards remotely located optical transceivers. Narrow-beam transmission with high directionality has been reported for indoor optical wireless communications [5]. Similarly, the use of narrow beams in underwater optical wireless communications enables high-sensitivity reception in scattering media, making them effective [6]. Galilean telescopic beam shapers can simultaneously generate narrow flat-top beams, thereby achieving low-loss beam shaping and underwater transmission [7].

In optical fiber communication, where narrow beams can be maintained in the longitudinal direction, wavelength division multiplexing (WDM) is initially used to achieve a high capacity. WDM is a superior method for transmitting data in high-density, large-capacity optical fiber transmission paths, making it an inevitable trend in optical wireless communications alongside narrow beams. Reflective, diffractive, and transmissive beam-shaped optical devices are also available. Nevertheless, a transmissive type is desirable for wavelength-division beam shaping, as it can be designed using passive optical components, supports high input-output power during beam shaping, exhibits wavelength independence over a wide bandwidth, and allows for input-output in the same beam path. A transmissive wavelength-division beam shaper is preferred as the wavelength-agile beam-shaping device.

In this study, we conducted underwater channel transmission experiments using single flat-beam-type visible light-band WDM signals by employing wavelength-agile Gaussian beam/narrow flat-beam converters. Furthermore, we attempted to maximize the transmission capacity over distance for two wavelengths using a TDHP scheme, which is an adaptive modulation scheme, to compensate for the differences in laser output intensity between wavelengths and losses during underwater channel transmission. We utilized Galilean telescopic beam shapers known for their characteristics of low wavelength dependence and ability to output in the same path. To the best of our knowledge, there have been no reports on simultaneous bulk conversion for multiple wavelengths using a single-beam converter for underwater optical wireless communication. In addition, our report represents the first instance of TDHP adaptive modulation applied to each wavelength of WDM signals in underwater optical wireless communication.

2. Broadband compatible flat beam shaping and wavelength unit time domain distance adaptive modulation

Figure 1 illustrates two configurations for beam shaping when multiple wavelengths are output through the same pathway: individual beam shaping and bulk beam shaping. Table 1 summarizes a comparison of the two approaches. Bulk beam shaping involves the combination of Gaussian beams initially emitted from lasers through a beam combiner, followed by simultaneous beam shaping at multiple wavelengths. This method offers advantages in terms of device size reduction and cost-effectiveness. However, individual beam shaping involves the separate beam shaping of Gaussian beams initially emitted from lasers at each wavelength, which allows for high flexibility in beam shaping for each beam. Bulk beam shaping is effective in environments with scattering media, such as underwater transmission channels, where narrow beams are preferred regardless of the wavelength.

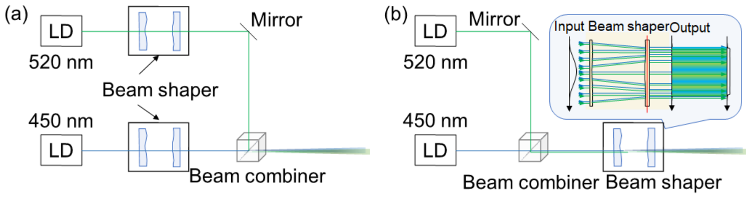

Fig. 1. Two beam shaping configurations (a) individual, (b) bulk.

Table 1. Comparison of two beam shaping

	Individual beam shaping	Bulk beam shaping
Number of device parts	Many	Few
Adjustment freedom for each beam	High	Low
Device cost	High	Low

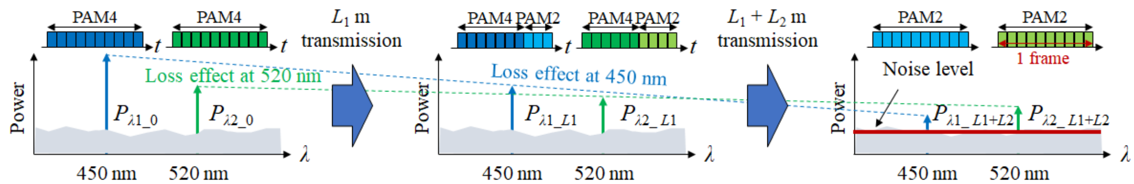

Fig. 2. Concept of underwater channel transmission distance adaptive TDHP modulation allocation for two wavelengths.

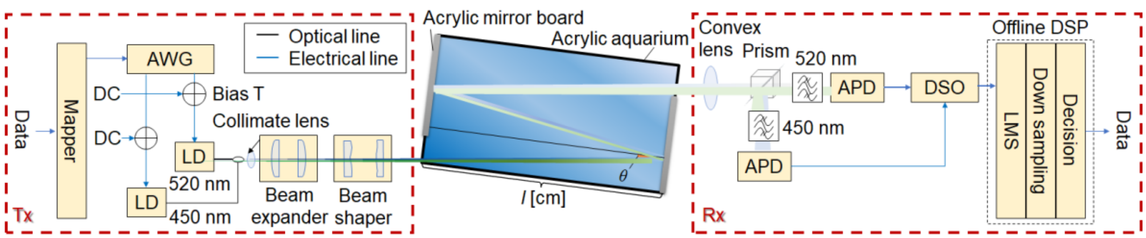

Fig. 3. Experimental setup.

Figure 2 depicts the principle of distance-adaptive all-wavelength optimal modulation allocation. In the visible optical band, both the laser output power and attenuation of the underwater channel vary with the wavelength. Consequently, the received power among the wavelengths varies with the transmission distance. Therefore, assuming constant noise power from the optical detector, the received signal-to-noise ratio (SNR) for each wavelength changes significantly with the transmission distance within the underwater channel. Hence, optimizing parameter p, which corresponds to the proportion of PAM4 modulation signals in the TDHP signal that is adaptively modulated for each wavelength, maximizes the transmission capacity.

3. Experimental setup

Figure 3 illustrates the experimental setup for underwater channel transmission of a flat beam carrying WDM-TDHP signals. On the transmitter side, the data bit sequence was converted into two types of TDHP signals, PAM2 and PAM4, using a mapper. This experiment used the TDHP signals with p parameters of 0.5, 0.75, and 1. The symbol sequences of the TDHP signals were output as electrical signals using an arbitrary waveform generator (AWG) with a DC component added by Bias-T. WDM-TDHP signals, modulated directly by two light sources with center wavelengths of 450 nm and 520 nm, were combined using a beam combiner and transformed into parallel light using collimating lenses. The Gaussian-shaped collimated light was shaped into a flat-beam profile using a beam expander and beam shaper. The beam expander and shaper insertion losses were both 0.8 dB.

A TDHP signal with a rate of 2λ × 312.5 Msymbols/s was propagated through an acrylic water tank (0.45 m × 1.2 m × 0.6 m × 0.01 m, height × length × width × thickness) filled with tap water. Following this propagation, the signal was reflected by an acrylic mirror and travels back and forth inside the water tank before being transmitted underwater to air. The transmission distance was adjusted by varying the number of reflections from the acrylic mirror.

Each beam was spectrally separated on the receiver side using a prism, and only the desired signals were extracted using optical bandpass filters corresponding to each wavelength. These signals were then converted into electrical signals by avalanche photodiodes (APDs). The electrical signals from each APD output were converted into digital signals using a digital storage oscilloscope (DSO). In the offline digital signal processing unit, the sampled signals were temporally equalized using a least mean square (LMS) algorithm, downsampled, and subjected to detection processing. The LMS algorithm was applied to a 15-tap finite-impulse response filter. Following detection, the received data bit sequence was reconstructed, and the error rate was calculated. This experiment assumes a Reed-Solomon error correction code with 7% redundancy, and the forward error correction (FEC) limit was set at a bit error ratio (BER) of 3.8×10^{-3}.

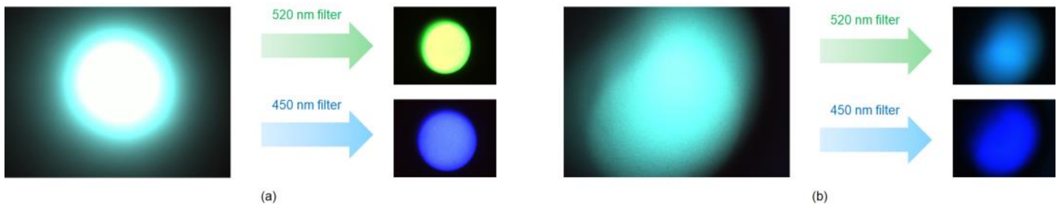

Fig. 4. Beam cross-sectional images before and after wavelength separation of WDM signal (a) 0 m, (b) 7.2 m underwater transmission.

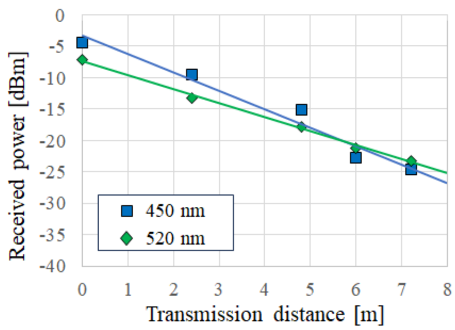

Fig. 5. Received power versus transmission distance.

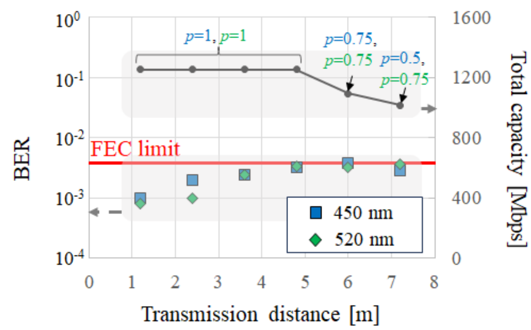

Fig. 6. BER and total capacity versus transmission distance.

4. Experimental results

Figure 4 illustrates color images taken with a camera of the WDM signals at 0 and 7.2 m, and the beam cross-section after filter separation. The color of the beam cross-section changes owing to the relative variation in power between the two wavelengths, as confirmed. Figure 5 illustrates the measurement results of received optical power as a function of transmission distance for a laser diode (LD) emitting light at 450 nm and 520 nm wavelengths. While the output from the beam combiner shows that 520 nm has higher power, it can be observed that as the transmission distance in the underwater channel increases, 450 nm becomes the higher-power wavelength. Generally, when using low turbidity tap water as the channel medium, it is expected that 450 nm would have lower transmission losses if the beam shapes were the same. However, this phenomenon is attributed to the fact that, in the case of post-beam shaping, the 520 nm wavelength is better shaped into a narrower beam. Generally, when tap water with low turbidity is used in the flow path, the transmission loss will be smaller at 450 nm if the beam shape is the same. However, the relationship may change if the beam shape is different. In this case, the 520 nm beam is shaped to be flatter and narrower than the 450 nm beam, which reduces distance attenuation.

Figure 6 illustrates the BER characteristics when maximizing the transmission capacity and achieving the FEC limit for the two-wavelength TDHP signal as a function of transmission distance. This simultaneously represents the total transmission capacity for the two wavelengths at each transmission distance. The optimization of the modulation for each wavelength demonstrated the ability to maximize the transmission capacity of the WDM-TDHP signal while transmitting over various distances.

5. Conclusions

We conducted experiments to demonstrate the feasibility of long-distance transmission in underwater channels by applying bulk beam shaping to two wavelengths separated by 70 nm within the visible light spectrum. Furthermore, we demonstrated the maximization of the transmission capacity for WDM with adaptive modulation using TDHP signals, considering the varying loss characteristics of the two wavelengths in an underwater environment.

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