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LED-Based Underwater Wireless Optical Communication for Small Mobile Platforms: Experimental Channel Study in Highly-Turbid Lake Water

WEI WEI, CHUNLEI ZHANG, WEI ZHANG, WEI JIANG, CHANG SHU, AND QIAO XIAORUI
Engineering College of Electronic, Naval University of Engineering, Wuhan 430033, China
Corresponding author: Wei Wei (haijungong@163.com)

ABSTRACT Underwater collaborative work between small mobile platforms (SMP) such as divers, litter submarine or AUV, requires a high data rate communication system which is compact, reliable, affordable and eye-safe. The high bandwidth of LED-based underwater wireless optical communication (UWOC) is an advantage. Artificial, emulated as well as simulated, turbid underwater channel has been studied recently, but no practical nature water. To fully meet the requirements of challenging turbid underwater channel scenarios for SMP, we demonstrated a green LED-based UWOC system up to a bandwidth of 3.4 MHz in a highly-turbid nature lake water. Through a contrast wireless optical communication (WOC) experiment in air, turbid water channel is observed to compensates the receiving signal amplitude attenuates after propagating a longer attenuation length due to multiple-scattered light caused diffusion, and thus to be more like a single-input multi-output (SIMO) system. From our experimental observation, the SIMO channel model could be employed not only in turbulent UWOC, but also in highly turbid UWOC. Moreover, turbid water channel is observed a "frequency selection" effect, thus LED with lower threshold voltage at higher frequency would optimize bandwidth and link range, and a robust pre-code for interference cancellation would be a well-direct choice to constructing different UWOC system in highly turbid water for SMP. Our finding will provide a new reference complementing the current LED-based UWOC systems in realistic water environment.

INDEX TERMS Underwater wireless optical communication, channel, turbid water, LED, wireless optical communication, single-input multi-output, visible light communication, small mobile platform.

I. INTRODUCTION

Underwater collaborative work between underwater small mobile platforms (SMP) such as divers, litter submarines or AUV, requires real-time and high data rate link for voice, data or video communication. AUV needs high-speed transmitting link to efficiently collect large amounts of data stored by underwater sensors [1]. Due to the small load capacity and limited power supply, SMP require these high data rate communication system to be compact, simple, reliable and affordable. It is often impractical to make a optical fiber connection between these underwater SMP, the high bandwidth of UWOC is an advantage.

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UWOC has became a hot topic in recent years, as it plays an important role in lake or river pollution monitoring, harbor oil control and maintenance, offshore explorations, and oceanography research [2]–[9]. Although tremendous progress has been made in the field of acoustic communication underwater, it is limited by narrow bandwidth, high latency and serious multipath effect [2]. All this has led to the proliferation of UWOC, especially in the blue/green region, as it provides much higher data rates than the traditional acoustic communication systems with significantly lower power consumption and simpler computational complexities for short-range wireless links [2].

At present, UWOC systems could be generally divided into two categories according to light source: laser-based and LED-based. Lasers are more capable of supporting higher data rates due to large modulation bandwidth (>1 GHz) than LED whose modulation bandwidth is almost less than 200MHz. Oubei *et al.* [10] employed 450-nm fiber-pigtailed laser diode (LD) directly encoded with an orthogonal frequency division multiplexed quadrature amplitude modulation (QAM-OFDM) data. A record data rate of up to 4.8 Gbit/s over 5.4m transmission distance was achieved, but the transmitter required an external modulator. In [11], the UWOC system successfully achieved a data rate of 500 Mbps through a 100 m tap-water channel. They used a pigtailed single-mode fiber 520 nm green LD, and the transmitter also required an external modulator. Shen *et al.* [12] demonstrated a high-speed UWOC link offering a data rate up to 2 Gbps over a 12-meter-long channel, and 1.5 Gbps over a record 20-meter-long underwater channel. A 450-nm laser diode (LD) and a Si avalanche photo detector (APD) was utilized in their experiment as well as the forward error correction (FEC) criterion was employed therefor the system is costly. Also 450-nm GaN blue LD provides the 64-QAM OFDM transmission up to 9 Gbps in their free-space visible light communication (VLC) demonstration in [13], and 12.4 Gbps ranged 1.7m UWOC in [14]. Tu *et al.* [15] experimentally demonstrated a 256 Gbps PAM4 UWOC convergent system which seems to be the highest speed UWOC transmission performances against current state-of-the-art. They adopted two-stage injection-locked red-light transmitters and the attenuation was so severe that transmission distance was very short even in clean water in this demonstration. In [16], a UWOC link distances up to 249.2 m in clear ocean water was achieved and that was the longest communication attenuation length ever reported under 1mJ single pulse energy. As a photon-counting receiver system with Reed-Solomon (RS) and low-density parity check (LDPC) codes was used, this system was too costly to be applied in underwater SMP. Based on a system design consisting of an ultraviolet (UV) laser for enhanced light scattering and a high sensitivity photo multiplier tube (PMT), a link was built with a data rate of 85 Mbps and a transmission distance of 30 cm using on-off keying (OOK) in emulated highly turbid harbor water in [17]. Although Laser-based systems have been demonstrated for long ranges, high data rate, there have been inadequacies. Laser is temperature dependent and easy damage due to over current. Some high power lasers take low reliability and some require cooling arrangements [9]. Further, they are costly and need tight pointing requirement. And, quite apart from that, laser is not eye safe to divers.

Due to incoherent optical beam and wide output beam divergence, LED-based systems transmission distance are limited, however, the implementations are low cost, require no special circuitry, and easier pointed, has been widely used in short range UWOC. In 2004, the Woods Hole Ocean Institution (WHOI) achieved 115Kbps of Irda protocol 1.0 communication in seawater using ordinary blue LED array, at a distance of 3.7m [18]. In 2005, Schill *et al.* [19] implemented 57 Kbps error-free data communication within 2m using visible light LED. In 2007, MIT [20] developed a small, lightweight, inexpensive and easy-to-operate prototypes that can work over a distance of 30m with a transmission rate of 1.2Mbps in clear water, and a distance of 9m with a transmission rate of 0.6Mbps in water with visibility of about 3m. In 2010, the group developed a second-generation prototype for long-range communications (named Aquaoptical II) 2.28Mbps over a transmission distance of 50 m in a pool experiment [21]. From 2005 to 2012 [22]– [25], a team from the North Carolina State University conducted several underwater blue-green light communication tank experiments, using the LED array as a light source and PIN as a photodetector. In 2013, Cossu *et al.* [26] used two low-cost LEDs arrays as optical transmitter and an APD as receiver achieving error free transmission 6.25 Mbit/s with Manchester coding, 12.5 Mbit/s with NRZ 8b/10b coding and 58 Mbit/s with Discrete Multitone modulation over 2.5 m distance. In 2016, Xu *et al.* [27] experimentally demonstrated an OFDM-based UWOC with blue LED over a 2 m clean water channel, achieving espectively net bit rates of 161.36 Mbps using 16-QAM, 156.31 Mbps using 32-QAM, and 127.07 Mbps using 64-QAM. Wang *et al.* [28] demonstrated a 25Mbps transmission system over 50 m distance in clear water using a blue LED and APD detection. In 2017, a LED-based modulation bandwidth achieved at about 160 MHz in tap water at an underwater distance of 0.6 m in [29]. In 2019, transmission over 46 m of LED-based UWOC within a 5 MHz range was demonstrated using multi-pixel photon counter [30]. To achieve higher transmitting rate or longer link range, photon detector like APD or photon counter were employed in these LED-based demonstrations, which requires complex control circuitry and are more sensitive to ambiance noise thus add the whole system complexity, reliability, as well as cost.

For eluding the pointing requirement in UWOC, a number of demonstration make use of photo-multiplier tubes (PMT) as their RX due to large field-of-view (FOV). PMT is used at the receiver to establish a communication link in a laboratory setup for 1 Mbps in non-return-to zero format for a distance of 3.66 m in a water tank simulating an ocean environment in the year of 2008, using a 405 nm laser diode [31]. After that, The trend to improve the data rate of UWOC systems by using LEDs has been followed in [32]–[38]. Basically these LED-based systems have insuffificient bandwidth and low transmission distance. Also an omni-directional UWOC basing laser and PMT in conjunction with diffuser in hemi-spherical configuration is presented in [32] for 100 m range at a data rate of 1 Mbps. But they were all LD-based transmitter. Arnon [33] studied the use of Silicon photo-multipliers (SiPMs) for LED-based UWOC and discussed their main interests and drawbacks, compared with PMT which could be partly regard as a LED and PMT-based UWOC system. In 2016, an error-free user rate of 8.68 Mb/s UWOC demonstration was performed in Narragansett Bay, employing both photon-counting PMTs are APDs of detectors and a low-power transmitter with a link with loss equivalent to 18 extinction lengths [39].

Since our ultimate aim is to offer a cost-effective and eye-safe UWOC system that meet SMP requirements, we need to satisfy the trade-off between transmitting length, bandwidth, system complexity, reliability, and cost. This could be accomplished by using LED and PMT, which are low-cost commercial devices with high reliability. In our previous work [40], we presented a robust digital LED&PMT-based UWOC link in a scope of 30 degree misalignment, and a data and voice communication was demonstrated with 4 Mbps over 8.4m and 1 Mbps over 22m under tap water in a 25-meters-long pool.

But, one of the biggest challenges for UWOC still originates from the fundamental characteristics of lake, river or sea water [40]. In realistic oceanic scenarios, water are turbid, naturally occurring impurities which absorb or scatter transmitting photons severely. SMP is more likely to work under shallow turbid water, such as river, lake, harbor and coast, where water quality would be poor and ambiance noise would be full. Previous studies [34], [41]–[46] on turbid water channel are based on water-tank experiments with different amounts of Maalox antacid. However, propagation distance is limited by the experimental set-up and the optical properties are different from nature water. Therefore, the experiment result is not accurate for the physical design of underwater wireless communications links. And all above LED-based UWOC demonstrations [18]–[30] were given under clean water. From the simulation results in [47], a LED-based UWOC which can be operated with a good received information quality under clean water would take a sharp turn for the worse in turbid water.

To fully benefit from the high capacity that LED-based UWOC could offer, especially in the presence of turbid water outdoor, an experimental study about natural impacts from turbid water on LED-based UWOC system is required. We developed a this analog UWOC demonstration to study channel of nature highly turbid water and construct UWOC system practical in highly turbid water. In this paper, digital coding and reshaping circuits are all removed to exclude the influence from digital circuits and a compact LED-based UWOC prototype is tested under turbid water in a natural lake and a comparative study is made between turbid water and air channels. Our work is to pave a way for improvements in LED-based UWOC by optimizing methods for SMP applications.

II. EXPERIMENTAL DETAILS

In [40], we reported the first voice and 1 Mbps data link of a robust LED-based UWOC with a misalignment of 30° over 24m long distance and presented the details of our LED-based UWOC prototype. More details can be obtained in our previous article [40]. In this paper, we will present a brief instruction and adjustments of our prototypes due to our purpose.

A. TRANSMITTER

It is well know that green-yellow-light(520-570nm) outperforms green-blue-light(450-500nm) in coastal and turbid waters due to higher chlorophyll and gelbstoff concentration [48]. Considering the balance between cost and performance, we chose an affordable 512nm green LED as our light source.

Generally speaking, drivers with large driving current for high-power lighting source (such as illumination source) are characterized by relatively low modulation speed (usually less than 10K), while drivers with high modulation speed for the light source (such as driver in blue-ray DVD) could normally sent small driving current through light source. Thus, a compact driver for green LED array with high drive current and high modulation speed is a key factor that limits the communication distance and transmission rates.

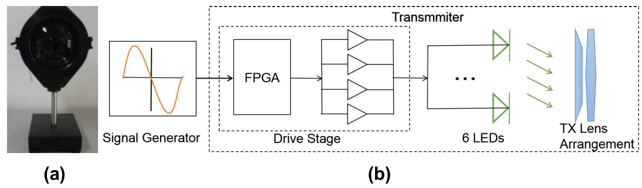

FIGURE 1. Prototype (a) & overview (b) of transmitter.

Our transmitter (TX) consists of a LED array, a drive stage and a TX lens arrangement (Figure.1). The LED array is composed of 6 Luxeon Rebel LEDs that emit 512 nm light. The total light output in radiant flux is 750mW. A compact drive stage are used to control the LED array. In this drive stage, four driving chips are exquisitely employed with multichannel parallel-driven technology and the average driving current of each LED is about 850mA with optical outputs approximately 125mW at 512nm. A Field-Programmable Gate Array (FPGA) in the drive stage controls and buffers the waveform from a signal generator and it then outputs the waveform onto the driving chip. The TX lens arrangement focus light to optical beam. It consists of two parts: a focus lens cluster and a collimation lens. The focus Lens cluster is a closely packed array of 6 diffractive lenses harness and redistribute each LED light source to form a point source. The collimation lens employed a plano convex lens to collimate the point source with a diameter of 12mm, focal length of 18.06mm and spot size of 12mm. Through the simulation of Zemax, the spot size was 1.72m and 2.6m at a range of 10m and 15m in the air, respectively, and the divergence angle is less than 5°. The optical path of the TX lens arrangement is shown in Figure 2.

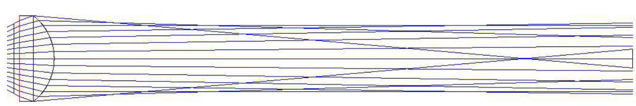

FIGURE 2. The optical path at transmitter by Zemax simulation.

B. RECEIVER

Our receiver (RX) prototype consists of a RX lens arrangement, a PMT, a gain adjuster (Figure 3).

In the RX lens arrangement, a Kepler optical structure is designed. According to our simulation of Zemax, the spot radius at the focal point is 3.9mm, and the luminance (optical

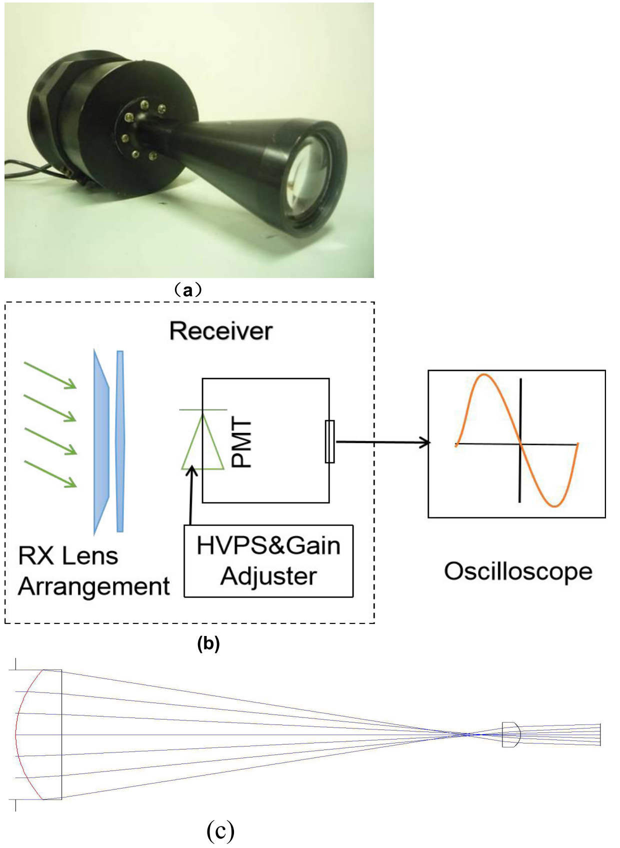

FIGURE 3. Prototype (a) & overview (b) of receiver, (c) is the optical path in receiver simulated by Zemax.

power) is uniformly distributed. In the RX lens arrangement, a Zolix narrow-band interference pre-filter is used to filter out the ambient noise light at the front end of PMT. PMT is characterized by high gain, low noise, high frequency response, large collection area, and moreover, it's an affordable choice for SMP. A Hamamatsu R7400U-01 PMT is adopted as the photo detector, which is powered by a compact high voltage power supply (HVPS) along with an gain adjuster. The response speed is 0.78 ns and the response sensitivity is 40 MA/w at 532 nm. In order to study the impact of turbid water channel, the transmitting and receiving waveform is analog without any digital shaping, modulating, coding or processing, to remove the inference from the modulating or digital signal processing (DSP) circuit. besides the working wavelength, turbid underwater channel is quite different from the air channel in attenuation magnitude and heavy scattering. For example, small change of link range is tolerable in VLC, but not in turbid UWOC, and the pointing requirement is tight in VLC while not so much in turbid UWOC. We hope to figure out differences like that and consequently construct UWOC system suitable in highly turbid water.

C. WATER CHANNEL

Simulated turbid water are of interest to researchers concerned with the optical attenuation of water. In an UV

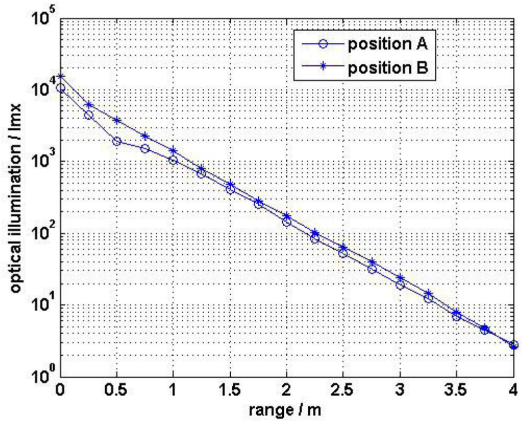

FIGURE 4. Horizontal attenuation in lake water.

laser-based UWOC [17], four types of ocean water were considered: clear seawater, coastal water, and two types of harbor water, emulated by adding precise quantities of commercial antacid to deionized water (DI). In our investigation, a lake test was directly carried out in a turbid lake in Hubei Province on September 28, 2019. Before the test, the water quality of the lake was measured at pm4:25 to pm4:53, and the weather was windy with the wind scale level 3 to 4 (3.4-7.9 m/s). The horizontal attenuation of the lake water was illustrated in Figure 4, which was measured by using an illuminometer in two different positions A and B in the lake respectively. The two results were much similar and the attenuation coefficient was approximately $2.1m^{-1}$. The results indicated that the water quality of the lake was very poor, which was, apparently, consistent with our naked eyes observation.

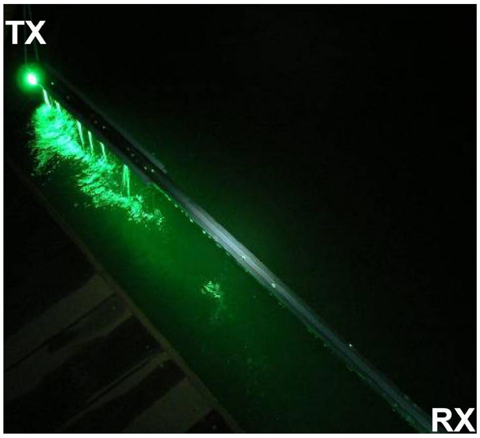

FIGURE 5. Experimental scene in lake.

D. EXPERIMENTAL SETUP

During the experiment, the transmitter and receiver were fixed to a metal straight rod about 10.5 m long (Figure 5) to meet tight pointing requirement, and the whole transmitter and receiver were completely submerged under about 0.5-meter-deep water. At the transmitter side, a LED array

TABLE 1. Attenuation coefficients for three ocean Water type from Petzold [53] and communication distances in our experiment.

Water type	Clear ocean water	Coastal ocean water	Turbid harbor
Attenuation coefficients from Petzold(m^{-1})	0.1514	0.399	2.195
our experiment attenuation length7.77	51.52	19.47	3.54
our experiment attenuation length5.67	37.45	14.21	2.58
our experiment attenuation length3.57	23.58	8.95	1.63

with the TX lens arrangement was mounted on an end of a metal straight rod. A signal generator was used to generate a sine waveform, and the wave stream was fed into the LED driver stage. At the end of the transmitted beam in the lake, the RX lens arrangement is used to capture photons in water and focus them onto the PMT. Then the waveform from the PMT was fed into an oscilloscope (OSC).

The receiver could not detect optical signals until shortening the link distance to 3.7 m. Then tests with various modulation frequencies were carried out over link distances of 3.7 m, 2.7m, 1.7m, respectively. Since in UWOC, the attenuation length (product of link distance and attenuation coefficient) is usually used to describe impacts of the water optical channel [49]–[51], attenuation lengths corresponding to our three communication tests are 7.77, 5.67 and 3.57.

J.T.Petzold is one of the pioneers in physical verification of UWOC. In 1968, he developed an underwater transmissometer for ocean survey work using a cylindrically limited beam [52]. In 1972, when one of his great far-reaching work in UWOC was published [53], in which volume scattering functions for three general types of natural ocean waters have been obtained and are presented here. The three types of water are deep clear oceanic water, near shore ocean water, and very turbid harbor water. Also included are the results of laboratory experiments using sea water, filtered fresh water, and artificial scattering and absorbing agents. After that, most of physical verification of UWOC are based on his work. In 1981, the UV submersible spectro radiometer had been employed to determine the diffuse attenuation coefficient for irradiance in the clearest natural waters with emphasis on the spectral region from 300 to 400 nm [54]. In [55], large photosynthetic life is found in the euphotic zone where chlorophyll is the main component of phytoplankton. This zone is up to 15 m in coastal water. In [56], the variation of chlorophyll with depth forms a skewed Gaussian profifile from surface to the bottom. In [57], an expression of concentration of colored dissolved organic matter and suspended scattering particles is discussed by the concentration of chlorophyll.

Distances corresponding to our three attenuation lengths are about: 51.32 m, 37.45m, 23.58m in clear ocean water, 19.47 m, 14.21m, 8.95m in coastal ocean water and 3.54 m, 2.58m, 1.63m in turbid harbor water.

Like in atmospheric channel, turbulence has an important influence in UWOC channel. Emulated as well as simulated turbulence has been studied in some literature [56]–[58]. However, it is not the subject matter and will not be discussed in this paper.

TABLE 2. Measured DC Voltage and Peak-peak value over different distances when the modulating frequency was 500kHz.

Link distance(m)	DC Voltage (V)	Peak-peak value (V)
1.7	5.445	1.8
2.7	1.714	0.5
3.7	0.091	0.04

III. RESULTS AND DISCUSSION

Different from laser, LED is drive by a threshold voltage(3.65V in our case) due to the P-I character, thus there is a DC component in output signal of photo detector. For a LED-based wireless optical communication system with intensity modulation/direct detection (IM/DD), there is a DC component in the received signal. It is always hoped that the DC component ''consumes'' less power, so that the received waveform peak-peak value(voltage amplitude from minimum to maximum in output signal of photo-detector) is higher. Consequently the signal-to-noise ratio (SNR) will be better. As analog waveform signals are transmitted in our link, the digital benchmarks like BER or transmitting rate is not a proper benchmark for communication evaluation. Instead, the SNR is widely accepted in analog wireless optical communication [58] The art of the peak-peak values and the DC components, which are closely related to the SNR, are carefully studied so as to save more energy in our underwater SMP scenario to improve the overall robustness. In this paper, two indications, the DC component and peak-peak value, are mainly discussed and they are extracted from received signals.

A. LAKE TEST RESULTS

From the measured attenuation coefficient $2.1m^{-1}$, we calculate DC components and peak-peak values using Beer's Law of exponential power loss model [44]. We compare the exponentially fitting calculations with measured DC components and peak-peak values in lake (Table 2), and find that they are quite close (Figure6 and 7) which verifies the measured attenuation coefficient 2.1 m^{-1}.

From our analysis of these lake test data, some interesting patterns are observed as following.

(1) Figure 6 and 7 show that for a specified signal frequency(500kHz in our case), the DC component and peak-peak value gradually decrease with the increase of communication distance, due to the water attenuation not surprisingly.

(2) The decreased SNR and low-frequency (LF) noises are the main reasons for limiting the transmission bandwidth, and no obvious time-domain signal broadening is observed which would cause inter-symbol interference (ISI). There are several reasons for that. Firstly, as the transmission distance

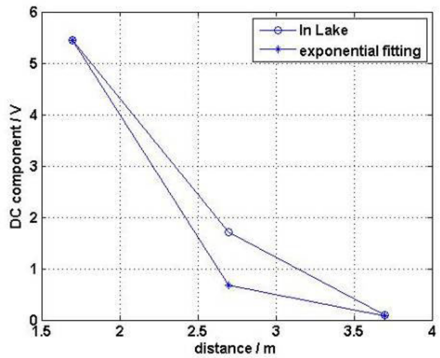

FIGURE 6. DC component versus distances at the frequency of 500 kHz.

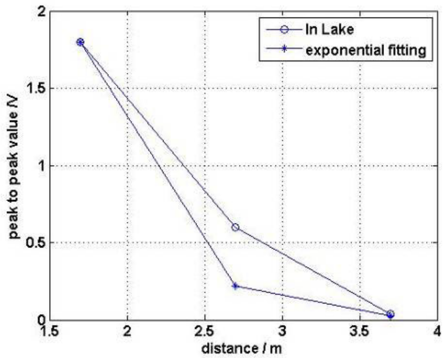

FIGURE 7. Peak-peak value versus distances at the frequency of 500 kHz.

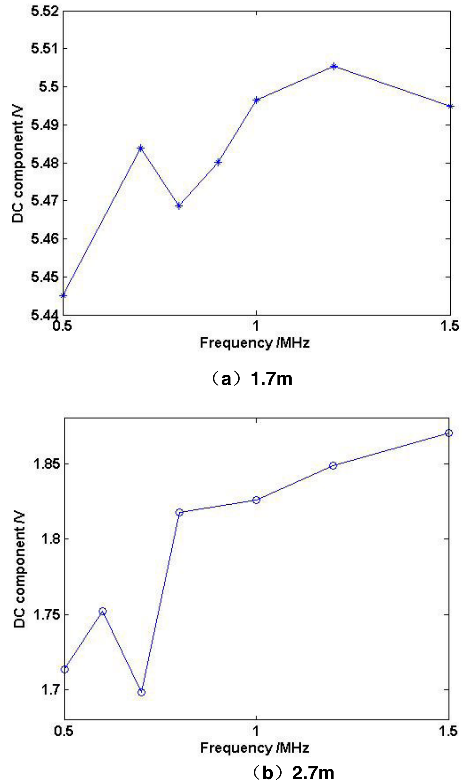

FIGURE 8. DC component versus signal frequency.

increasing, the SNR decreases and the signal quality deteriorated. Secondly, in Figure 6, 7 and 8, it can be observed that there are LF noises in the signal, which increases gradually with the increasing signal frequency. Over the communication distance of 3.7 m, these LF noises distorted received signal when the signal frequency approached to 500 kHz. Over the communication distance of 2.7 m, although there was no ISI observed in the time-domain waveform of the signal, these LF noises distorted received signal when the signal frequency was up to 1.5MHz. From Figure 7 and 8, there is no obvious ISI due to waveform time-domain broadening is observed to limit transmission rate in our tests over three distances.

We extracted the DC components from received signals at a range of 1.7m and 2.7 m at specified frequencies (Figure 8), and the following patterns can be observed:

(3) The DC component of the received signal increases with increasing signal frequency.

(4) The longer the underwater communication distance, the faster the DC component increases with the increasing signal frequency, that is to say, for the same increment of frequency (500 kHz to 1.5 MHz in this paper), the longer the communication distance (2.7 m in this paper), the more the DC component increases. We normalized these DC components and found that the DC component at a range of 1.7m increases with frequencies from 500 kHz to 1.5 MHz by 0.01dB, and the increment at a range of 2.7m communication is 0.1dB, a difference of an order of magnitude. We suppose that is due to the modulation character of LED threshold voltage: the threshold voltage shifts to higher value with the increasing modulation frequency.

The peak-peak values at different frequencies are also extracted according to three groups of signal data: 1.7 m, 2.7m and 3.7m. From data shown in Figure 12, the following features are obtained:

(5) The peak-peak value decreases as the modulating frequency increase. The main reason is that, for a certain total received optical power, the DC component increases with the increasing modulating frequency, while the corresponding signal peak-peak value decrease. That is why the SNR decreased, which was an important factor to limit the transmission rate.

(6) The peak-peak value decreases as increasing modulating frequency with a "frequency selection" effect: in Figure 9(a) the decrease is sharp at low frequency range (from 500 kHz to 1 MHz) and gentle at higher frequency (1 MHz to 1.5 MHz). This pattern can be also observed in Figure 12(b).

(7) The longer the link distance, the slower the decrease of peak-peak value with modulating frequency. As shown in Figure 9(a), the variation curve of 2.7 m is obviously flatter than that of 1.7 m.

The received SNR is extracted from the received voltage amplitude signal (Figure 9,10).

(8) The SNR is about 18.4dB with the frequency 500kHz and falls to 13.4dB with the frequency 1.5MHz over 1.7m while it reduces from 13.17dB to 9.83dB over 2.7m (FIGURE

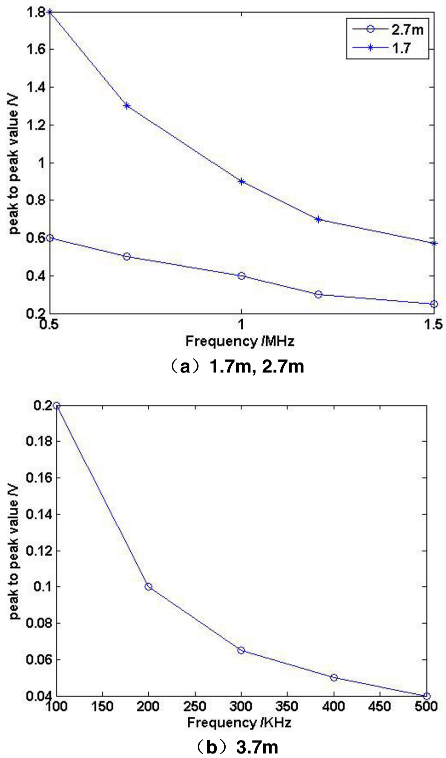

FIGURE 9. **Peak-peak value versus modulating frequency.**

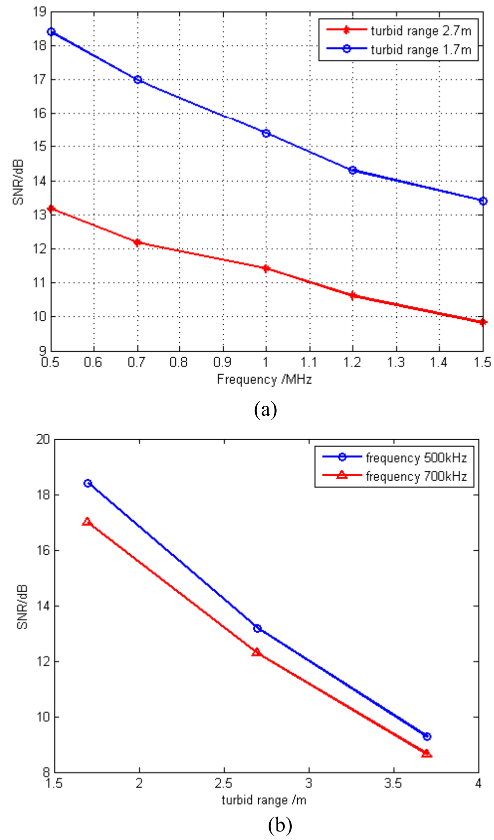

FIGURE 10. **(a) The SNR versus modulating frequency. (b) The SNR versus TX/RX range in turbid water.**

10). The falling SNR is mainly determined by the decreasing of the peak value and the photoelectric responsibility of PMT. There is a ''frequency selection'' effect: the downtrend is sharp at low frequency range (from 500 kHz to 1 MHz) and gentle at higher frequency (1 MHz to 1.5 MHz). This pattern can be also observed in the pattern(6).

(9) At the the frequency of 500kHz, the SNR is about 18.4dB over 1.7m, 13.17dB over 2.7m, 9.28dB over 3.7m while they are 16.99dB, 12.28dB, 8.64dB at the the frequency of 700kHz. The SNR declines 5.23dB from 1.7m to 2.7m while that is 3.89dB from 2.7m to 3.7m, which is smaller than the estimation of Beer's Law of exponential power loss model. We calculated the SER based on OOK modulation, the limitation SER of 10^{-3} was still hold at the SNR of 9.6dB.

B. INDOOR AIR COMPARATIVE EXPERIMENT

In order to study the impact of underwater optical channel on communication, a comparative experiment indoor was performed in air over a range of 1.7 m with same modulating frequencies. Both sets of data were measured with the PMT directly. Consequently the differences show the speciality of turbid underwater channel.

In order to avoid PMT overload in the air experiment, the gain of PMT was adjusted to very small, thus the ordinates in Figure 11,12 between the air and lake water are incomparable directly. To exclude the difference in gain, all results were normalized by respective standards values (the DC component, peak-peak value and SNR at the frequency of 500 kHz were taken as the standard values). Variation patterns of the normalized DC component and peak-peak value can be used to study the difference of impacts on communication in air and turbid water channels. Results are as followed.

Some patterns are obtained as following:

(10) The DC component grows with the increasing modulating frequency, and this pattern exists both in air and turbid water channel over various distances, indicating that it is mainly determined by the modulating characteristics of the LED itself.

(11) The growth of DC component in turbid water is much slower than that in air. From 500kHz to 3.5MHz, the growth in water is about 0.025 dB, while that in air is about 0.08dB, rising about three times faster. The peak-peak value declines in turbid water at slower rates than that in air. From 500kHz to 3.5MHz, its loss in air is about 2.2dB, while that in turbid water is only about 0.9dB, which is more than two times different.

From patterns in (3)(5)(6)(8)(10), we can come to a conclusion that, with the increasing modulating frequency, the SNR decreases, which is mainly determined by the frequency modulating characteristics of the LED source. So LED with lower threshold voltage at higher frequency will consume less power supply under turbid water for SMP UWOC.

From patterns in (1)(2)(3)(4)(7)(9)(11), the following conclusions can be drawn: the turbid water channel has a

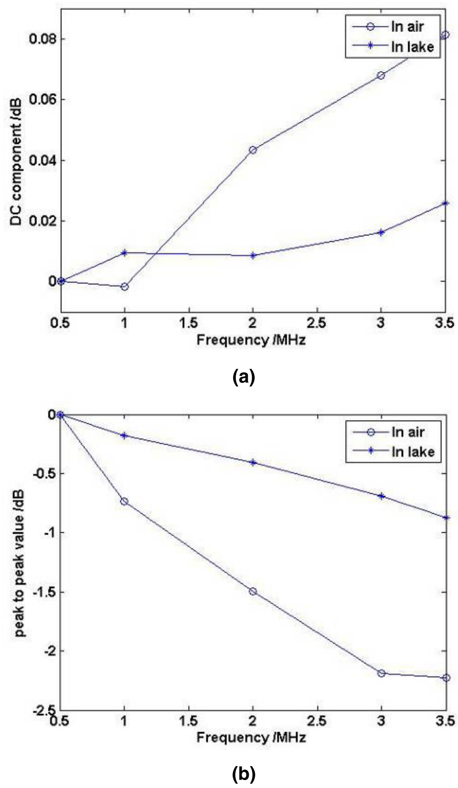

FIGURE 11. DC component (a) & Peak-peak value (b) versus frequency.

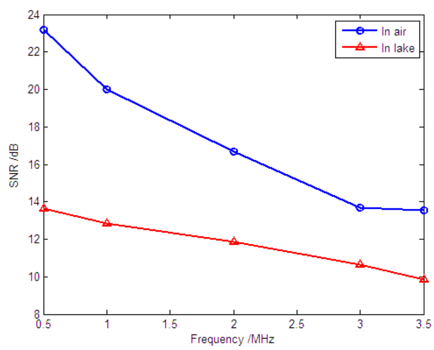

FIGURE 12. SNR versus frequency.

attenuation effect on the received signal, which is unsurprising. In air, there is a significant drop in the peak-peak value since the probability of scattering is low and there is little multiple scattering which generally agrees with the Beer's law. Compared with the air channel, the turbid water channel puts a drag on rise and fall of the received signal when the frequency varies, but this ''drag'' effect fades as the underwater communication distance increases. In other words, after propagating a longer attenuation length, the amplitude attenuates slower in turbid water. The high turbidity is supposed to causes multiple-scattered light to dominate, and due to the additional collection of multiple-scattered light that scatters into the receiver FOV, the received signal, are compensated, which has previously been observed in [61] and roughly matches the Monte Carlo simulation in [62]. To some extent, the effect of diffusion in turbid water makes the point-to-point UWOC into a SIMO system and thus compensates the receiving signal power. A robust pre-code for interference cancellation would be a well-direct choice for higher data rate LED-based UWOC to constructing different UWOC system in highly turbid water. From our experimental observation, the SIMO channel model could be employed not only in turbulent UWOC, but also in highly turbid UWOC. It's only a qualitative analysis, admittedly, our observations specific to receiving signal are preliminary, based on limited data in only a few groups, lack of comparison experiment in clean water, more numerical analysis at various frequencies need be done to make a quantitative evaluation for the highly turbid water channel capacity. But we believe, our observations is essential for evaluating the UWOC link budget in highly turbid water.

IV. CONCLUSION

We have demonstrated a green LED-based UWOC system up to a bandwidth of 3.4 MHz in a highly-turbid water channel outdoor. An effective communication link with an attenuation length of 7.77 still holds. Through a contrast experiment with air channel, turbid water channel is observed to compensate the receiving signal amplitude attenuates after propagating a longer attenuation length due to multiple-scattered light caused diffusion, and thus to be more like a SIMO system. We believe our experimental observation, that turbid water channel would be more like a SIMO system, would provide a new reference to address SIMO detection problem over turbid UWOC. Actually, SIMO detection over turbid UWOC is becoming a developing field and there are growing theoretical researches in recent years [63]–[65]. LED with lower threshold voltage at higher frequency would optimize bandwidth and link range and a robust pre-code for interference cancellation would be a well-direct choice to constructing different UWOC system in highly turbid water. We believe that our LED-based UWOC demonstration in a highly-turbid water will provide a practical understanding for the current LED-based UWOC systems, especially in terms of realizing stable, affordable, compact and high-speed WOC for SMP scenarios under turbid water.

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WEI WEI received the B.S. degree, the M.S. degree in networks engineering, and the Ph.D. degree in telecommunication engineering from the Naval University of Engineering, Wuhan, China, in 2005, 2007, and 2011, respectively. His current research interests include development of underwater optical wireless communication, ocean information networks, fiber optical networks, communication power supply, structuring data, and power supply integrated system using submarine fiber mesh networks.

CHUNLEI ZHANG received the B.S. degree and the M.S. degree in telecommunication engineering from the Naval University of Engineering, Wuhan, China, in 2005 and 2009, respectively. His main current research interests include ocean information equipment and ocean information networks.

WEI ZHANG received the B.S. degree in telecommunication engineering and the M.S. degree in information engineering from the Naval University of Engineering, Wuhan, China, in 2005 and 2009, respectively. His main current research interest includes information management.

WEI JIANG received the B.S. degree and the M.S. degree in telecommunication engineering from the Naval University of Engineering, Wuhan, China, in 2005 and 2010, respectively. His main research interest includes ocean computer engineering.

CHANG SHU received the B.S. degree in automation engineering and the M.S. degree in computer engineering from the Wuhan University of Technology, Wuhan, China, in 2004 and 2006, respectively. His main research interest includes submarine optical fiber engineering.

QIAO XIAORUI received the B.S. and M.S. degrees in computer engineering from the China University of Geosciences, Wuhan, China, in 2006 and 2008, respectively. His main research interest includes submarine optical fiber engineering.