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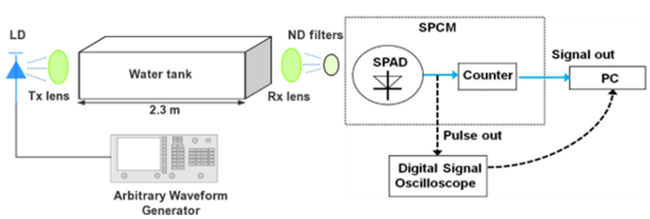

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Toward Long-Distance Underwater Wireless Optical Communication Based on A High-Sensitivity Single Photon Avalanche Diode

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Abstract: In this study, we built a single photon avalanche diode (SPAD) receiver based underwater wireless optical communication (UWOC) system. The bit error rate (BER) and signal-to-noise ratio (SNR) performance of UWOC with different distances and data transmission rates were obtained. Based on the water attenuation coefficient of 0.12 m^{-1}, a series of neutral density (ND) filters were exploited to attenuate the light output power from the blue laser diode (LD) to simulate the long distance UWOC. The maximum estimated distances of 144 m and 117 m with corresponding BERs of 1.89×10^{-3} and 5.31×10^{-4} at data transmission rates of 500 bps and 2 Mbps were acquired in UWOC system using on-off keying (OOK) modulation scheme, respectively. Furthermore, we compared the differences between free-space and underwater channels, and a divergence angle of $\sim$1.02 mrad was measured experimentally at a distance of 50 m in the free space. The long UWOC distances obtained in this study partly benefit from high sensitivity SPAD, the small laser divergence angle and low light attenuation. This study provides an approach to achieve long distance UWOC using SPAD.

Index Terms: Underwater wireless optical communication (UWOC), single photon avalanche diode (SPAD), laser, on-off keying.

1. Introduction

High-Sensitivity and long-distance underwater wireless optical communication (UWOC) has been paid significant attention recently by lots of researchers [1]–[7]. On account of potential advantages of low cost, low latency and high safety, UWOC is considered to be an important alternative candidate to acoustic communications and radio frequency (RF) communications [1]–[10]. It has been proposed as an important communication technology for future applications in oceanography exploration and detection activities. However, the underwater channel is very complex since water molecules and other particulates, such as salt and chlorophyll, strongly absorb and scatter light

TABLE 1
Comparison of Recent Experimental UWOC Systems in the Literature

Group	Type of light source	Type of receiver	Light output power	Modulation scheme	Distance (m)	Data rate
C. Shen et al. [1]	450 nm LD[a]	APD[b]	51.3 mW	NRZ-OOK[f]	20	1.5 Gbps
X. Liu et al. [2]	520 nm LD	APD	19.40 mW	NRZ-OOK	34.5	2.70 Gbps
M. Doniec et al. [22]	470 nm LED	APD	10 W	DPIM[g]	50	2.28 Mbps
Y. Huang et al. [23]	450nm LD	APD	44.4 mW	QAM-OFDM[h]	10.2	10.8 Gbps
J. Shen et al. [24]	450 nm LD	MPPC[c]	N/A[e]	PPM[i]	46	5 Mbps
J. Wang et al. [25]	520 nm LD	APD	7.25 mW	NRZ-OOK	100	500 Mbps
This work	450 nm LD	SPAD[d]	22.9 mW	NRZ-OOK	144 117	500 bps 2 Mbps

[a]LD represents laser diode.
[b]APD represents avalanche photo diode.
[c]MPPC represents multi-pixel photon counter.
[d]SPAD represents single photon avalanche diode.
[e]N/A represents not applicable.
[f]NRZ-OOK represents non-return-to-zero on-off keying.
[g]DPIM represents discrete pulse interval modulation.
[h]QAM represents quadrature amplitude modulation; OFDM represents orthogonal frequency-division multiplexing.
[i]PPM represents pulse position modulation.

during the transmission [4]–[6], [11]–[16]. As a result, high attenuation in seawater has made it difficult to achieve long-distance and high-speed UWOC.

In free space, high-bandwidth diodes with different wavelengths can be used for high-speed communication [17]–[19]. However, light attenuation varies with the wavelength in UWOC. Due to relatively low light attenuation in the blue-green spectrum window [3], [6], blue and green laser-diodes (LDs) and light-emitting diodes (LEDs) have been widely used in UWOC systems. Optical receivers typically used in UWOC systems are positive intrinsic negative (PIN) diodes and avalanche photodiodes (APDs). However, a gain-dependent excess noise source generated by avalanche multiplication in an APD limits the maximum gain [20]. A transimpedance amplifier (TIA) is normally used for electrical signal amplification, but it also produces thermal noise. Single photon avalanche diode (SPAD) is an APD operating in Geiger-mode. Since a TIA is not required and SPADs will not create related noise sources, the sensitivity of SPADs will not be reduced [21]. SPADs can be used to detect individual photons, suitable for low-power and long-distance optical communications.

Recent experimental UWOC systems in the literature with different data rates and transmission distances are summarized and compared in Table 1. M. Doniec [22] and C. Shen *et al.* [1] achieved 50-m and 20-m UWOC at data rates of 2.28 Mbps and 1.5 Gbps with discrete pulse interval modulation (DPIM) and OOK modulation, respectively. A study with a distance of 34.5 m and a data rate of 2.7 Gbps in water using a green laser was demonstrated experimentally by X. Liu *et al.* [2].

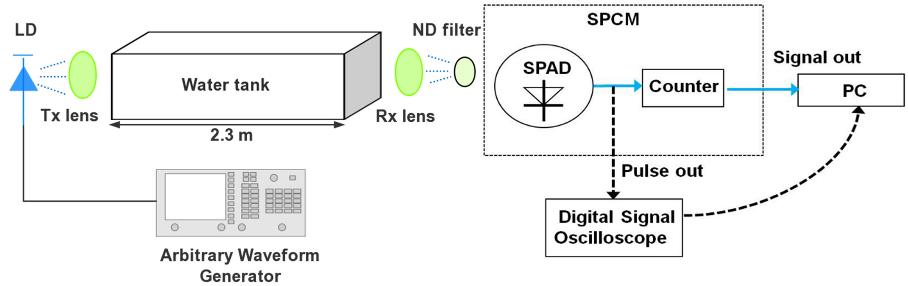

Fig. 1. Experimental setup of the proposed UWOC based on a blue LD and a SPAD receiver.

Y. Huang *et al.* used quadrature amplitude modulation orthogonal frequency-division multiplexing (QAM-OFDM) modulation to achieve a 10.8 Gbps data rate over a distance of 10.2 m [23]. Recently, J. Shen *et al.* [24] experimentally achieved a 46 m UWOC with pulse position modulation (PPM) at a data rate of 5 Mbps based on a 450 nm LD and a multi-pixel photon counter (MPPC) receiver. Later, a UWOC link with a distance of 100 m and a data rate of 500 Mbps using a 520 nm green laser was experimentally achieved by J. Wang *et al.* [25]. The longest distance of about 500 m was theoretically proposed by C. Wang *et al.* [26] with a SPAD-based receiver and a 532 nm LED at a data rate of 1 Mbps, but it has not been experimentally achieved yet.

In this study, a blue LD was used as the light source, and a SPAD-based receiver was used as the detector in the UWOC system. A blue LD provided sufficient light output power, low divergence angle and thus low attenuation. Meanwhile, SPADs with high sensitivity could increase the sensitivity of the whole UWOC system. A series of neutral density (ND) filters were exploited to attenuate the light output power from the blue laser diode (LD) to simulate the long distance UWOC. The maximum estimated distance of 144 m with a corresponding BER of 1.89×10^{-3} at a data transmission rate of 500 bps was acquired in a UWOC system using an on-off keying (OOK) modulation scheme. To prove estimated distances are acceptable, the difference between the underwater channel and free-space channel was compared, which has rarely been reported. Since the divergence angles in water were similar to that in free space, an experiment at a free-space distance of 50 m was used to estimate the divergence angle in the water. The change of the attenuation coefficient with the divergence angle was also studied, which further shows the superiority of the small laser divergence angle. As we all know, communication between facilities such as the underwater vehicles and the airborne terminals is a very important UWOC application scenario, where water/air interfaces exist. Therefore, it is important to study both the water channel and the free space channel.

2. Experimental Setup and Details

The experimental setup of a blue LD and a SPAD receiver based UWOC system is schematically shown in Fig. 1. The single photon counting module (SPCM) is mainly made up of a SPAD and an internal counter. At the transmitter side, the pseudo-random binary sequences (PRBS) generated by MATLAB program were loaded onto the arbitrary waveform generator (AWG2021) to drive a 450 nm LD (Thorlabs, PL450B). A non-return-to-zero on-off keying (NRZ-OOK) modulation scheme was used. After being collimated by a lens with a size of M7 $\times$ 5.5 mm and a focal length of 9.8 mm, blue light from an LD was transmitted through a water tank with a length of 2.3 m. On the receiver side, the transmitted light beam was focused by a Fresnel lens, whose focal length and diameter are both 10 cm. A series of neutral density (ND) filters with different transmittances of 0.01%, 0.1%, 1%, 20% and 40% were used to attenuate the receiving light. An SPCM with high-sensitivity was placed at the focal point to collect the output light and generate photoelectric conversion. The signal output terminal of SPCM outputs the signal from the internal counter, while the pulse output

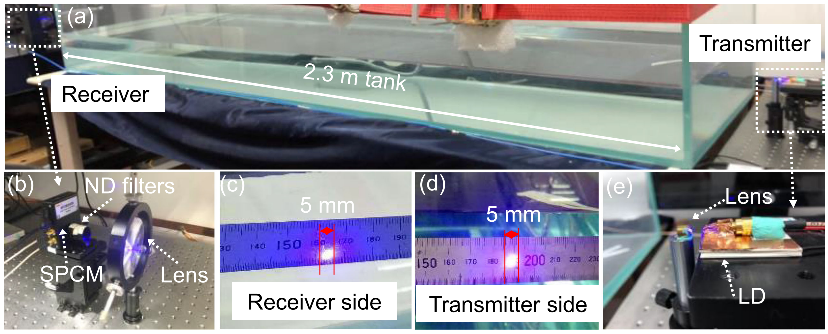

Fig. 2. A SPAD receiver based UWOC system setup: (a) the transmission link, (b) the SPCM receiver containing a SPAD and an internal counter, (c) the laser spot at the receiver side, (d) the laser spot at the transmitter side, and (e) the packaged 450 nm blue LD transmitter.

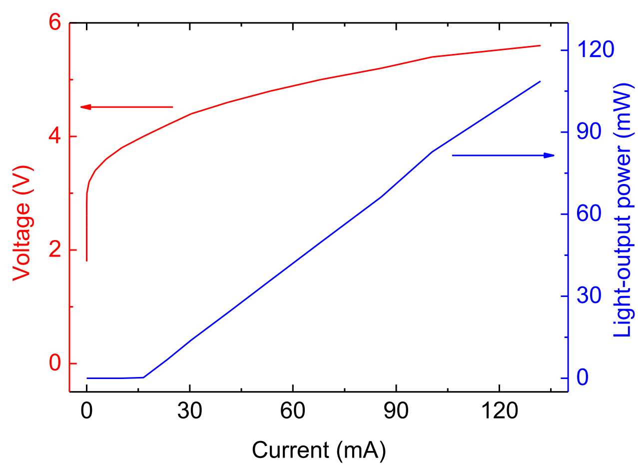

Fig. 3. The V-I and P-I characteristics of the 450 nm blue LD.

terminal of SPCM outputs the pulses from SPAD. At data rates below 500 kbps, the signal was obtained from the internal counter and further processed by a computer. At data rates higher than 500 kbps, the output pulses were obtained with a digital signal oscilloscope (DSO) and further processed by a MATLAB program in the PC. The light output power was measured at the receiver side with an optical power meter. The BER was further calculated by a MATLAB program. The images of a UWOC system with a SPAD-based receiver are shown in Fig. 2. Fig. 2(a) shows the transmission link including the transmitter, a 2.3-m length tank with water inside and the receiver. Fig. 2(b) shows the SPAD-based receiver side. Fig. 2(c) and (d) show the laser spot at the receiver side and transmitter side. The laser spot diameters at the transmitter and receiver sides were both 5 mm, which can be explained by the high collimation of LD. The maximum count rate of the SPAD-based receiver is 28 MHz and the dead time is 35 ns. The transmitter side of the proposed SPAD based UWOC system is shown in Fig. 2(e). The data transmission rate varies from 500 bps to 2 Mbps. The optical output power at the transmitting side is 22.9 mW, and the laser spot diameter is 5 mm. The transmitted NRZ-OOK signal is a PRBS with a standard pattern length of 2^7-1 bits.

3. Results and Discussion

Fig. 3 shows the voltage versus current (V-I) and light output power versus current (P-I) characteristics of the 450 nm LD. As can be seen from Fig. 3, the threshold current of the LD is about 17 mA

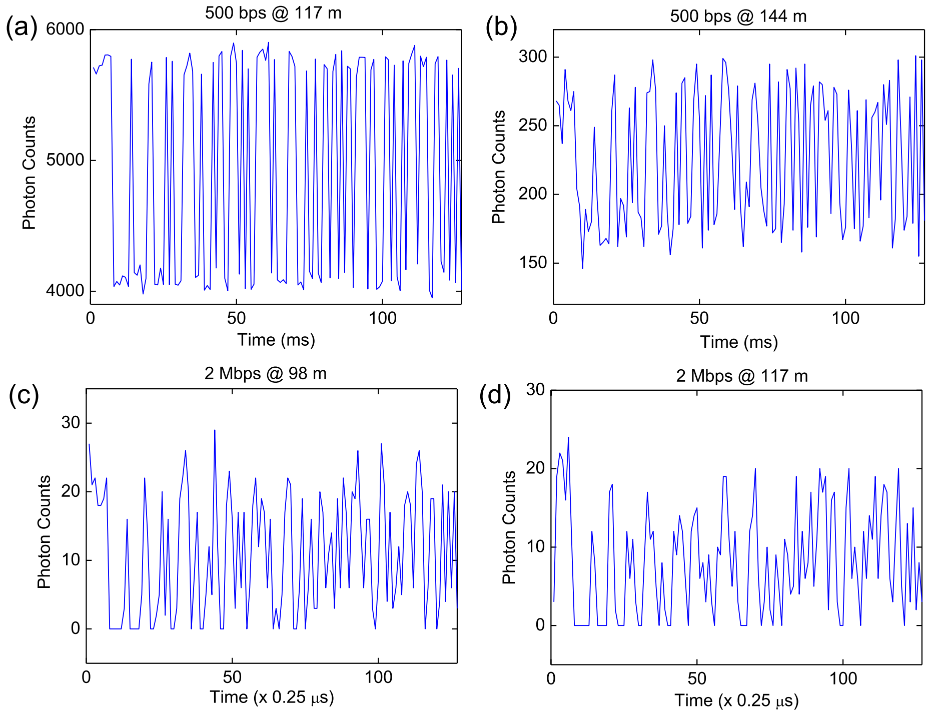

Fig. 4. The received photon counts per symbol at the data rates of 500 bps at (a) 117 m and (b) 144 m, and 2 Mbps at (c) 98 m and (d) 117 m.

at 4 V. According to the P-I characteristics, the corresponding operation current at the transmitting side is about 40 mA at the light output power of 22.9 mW for LD-based UWOC system in this work.

The underwater channel is very challenging due to the absorption and scattering caused by various substances in seawater. The link loss of water channel can be calculated according to the Beer-Lambert law:

$$I = I_0 e^{-cx}, \tag{1}$$

where I_0 and I are the incident optical power before and after passing through a water channel, c is the attenuation coefficient with a unit of m^{-1} and x is the channel length. To eliminate the influence of the air-glass-water interface, we tested the optical power at the receiving end in a 2.3-m tank with and without water at the same power of the transmitter, respectively. We assume the light attenuation through the tank with water as light passing through the tank without water and then passing through 2.3 m water. Therefore, we can regard optical powers at the receiving side in conditions of the tank without and with water as I_0 and I at the same transmitter power of 22.9 mW, which are 15.99 mW and 12.07 mW, respectively. From the experimental 2.3-m water tank and formula (1), we can get the attenuation coefficient c of 0.12 m^{-1}. The coefficient is slightly lower than the reported value [27], resulting from better optical alignment. With low attenuation coefficients, the link loss of the optical output power is decreased, so higher receiving optical power and longer distances can be obtained. The UWOC distances of this work were estimated by formula (1), using the experimental attenuation coefficient c of 0.12 m^{-1} in the 2.3-m water tank and the attenuation ratio (I/I_0) generated by the ND filters.

Fig. 4 shows the received photon counts per symbol at the data rates of 500 bps at distances of 117 m and 144 m, and 2 Mbps at distances of 98 m and 117 m. The average received photon counts at the data rates of 500 bps at 117 m and 144 m, and 2 Mbps at 98 m and 117 m are 4811, 217, 10.91 and 8.12, respectively. The energy of a photon is calculated to be 4.42×10^{-19} J [28].

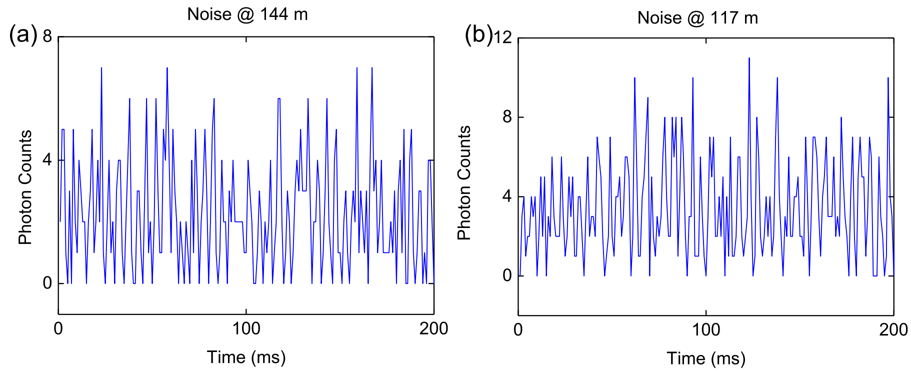

Fig. 5. The noise photon counts per symbol at the distances of (a) 144 m and (b) 117 m.

TABLE 2
UWOC Data Rate and Link Distance Using a SPAD

Data rate: 500 bps	Distance (m)	117.43	136.62	144.25
	BER	0	0	1.89×10^{-3}
Data rate: 2 Mbps	Distance (m)	98.24	104.02	117.43
	BER	0	3.94×10^{-4}	5.31×10^{-4}

At the distance of 117 m and the data rate of 2 Mbps, the total energy of received 8.12 photons is 3.59×10^{-18} J. Since the time used to transmit these photons is 0.25 μs, the optical power is then calculated to be 1.44×10^{-11} W. The minimum detectable power of the SPAD is even lower as 0.14 fW. In comparison, the minimum detectable optical power of a typically used APD is several nWs, which is about 10^7 higher than that of the SPAD. It can be seen that the sensitivity of the SPAD is much higher than an APD. In Fig. 4(a) and (b), as the distances decrease from 144 m to 117 m, the attenuation ratio provided by ND filters decreases from 2.5×10^7 to 10^6, which results that average photon counts decrease above 20 times. In Fig. 4(c) and (d), the signal noise ratio (SNR) can be calculated by the formula [29]:

$$SNR = \frac{n_1 - n_0}{n_0}, \tag{2}$$

where n_1 represents the average photon counts for the symbol “1”, and n_0 represents the average photon counts for the symbol “0”, which can also represent photon counts of noise. The values of the noise photon counts were collected with the SPAD at the data transmission rate of 0 Mbps. In Fig. 4(c), the average received photon counts of n_1 and n_0 are 19.38 and 2.42, respectively. The SNR is calculated to be 7 dB. In Fig. 4(d), the average received photon counts of n_1 and n_0 are 13.5 and 2.27, respectively. The SNR is calculated to be 4.95 dB. As the distance increases, the received signal photon counts of n_1 decreases, and SNR decreases. The noise photon counts are further tested and shown in Fig. 5. Fig. 5(a) and (b) show the noise photon counts per symbol at the distances of 144 m and 117 m, with the corresponding average noise photon counts of 2.34 and 3.41. It can be seen that the noise level is pretty low for our UWOC system, which is important to improve the SNR. Obviously, as the data rate increases, the maximum achievable transmitting distance decreases, and the average received photon counts decrease as well. The reason is that the increased data rate results in decreased SNR and requires higher response speed.

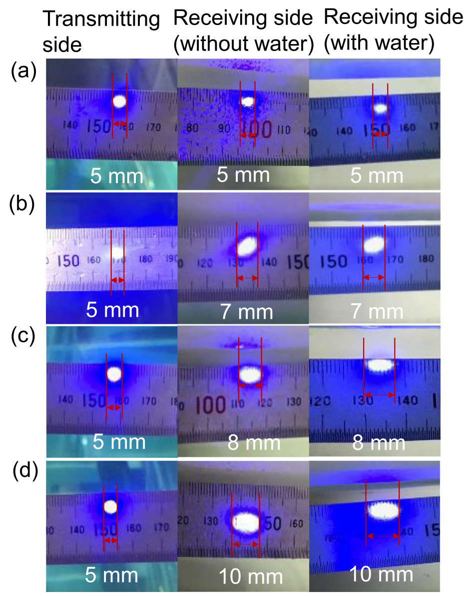

Fig. 6. The laser spot sizes of receiving sides with and without water in a 2.3-m tank measured with diameters of (a) 5 mm, (b) 7 mm, (c) 8 mm, and (d) 10 mm.

The data rate with corresponding BER and UWOC link distance is shown in Table 2. The maximum estimated distances of 144 m and 117 m with corresponding BERs of 1.89×10^{-3} and 5.31×10^{-4} at data transmission rates of 500 bps and 2 Mbps were acquired in a UWOC system, respectively. This result demonstrates that employing a SPAD can effectively promote the development of long-distance UWOC.

To further understand the underwater channel effect, we compared the difference between underwater and free space light beam size change, as well as the effect of the divergence angle. The laser spot diameters at the transmitting side which are both $\sim$ 5 mm and receiving sides were measured and shown in Fig. 2(d) and (c), respectively. Owing to the high collimation of LD, the laser divergence angle can be hardly seen at the short transmission distance.

The laser spot sizes and corresponding pictures at the transmitting side and receiving side with and without water in a 2.3-m tank are shown in Fig. 6(a)–(d). From our measurement, the laser spot sizes in the 2.3-m tank with water are the same as those without water at small divergence angles. Therefore, we assume that the free space and underwater beam divergences are similar at the small divergence angle in our experiment, and tested the divergence angle at 50-m free space to estimate the underwater beam divergence.

In Fig. 6, different divergence angles are compared. The optical setup in Fig. 7 is similar to the optical setup with the minimum divergence angle in Fig. 6(a), which is an extension test for the divergence angle at a long distance. However, it is tested only in the free space channel due to the experimental condition limitation, but it is also useful for estimating the communication distance in the water. We tested the divergence angle in a 50-m corridor using the 450 nm blue LD. The picture of the experimental setup for measuring the laser divergence angle in the 50-m corridor is shown in Fig. 7(a). The schematic diagram to calculate the laser divergence angle is shown in Fig. 7(b). Assuming that the divergence angle is the same at different distances, the divergence angle of θ can be determined by the formula:

$$\theta = 2 \arctan\left(\frac{D_R - D_T}{2L}\right), \tag{3}$$

where θ represents the laser divergence angle, D_T is the laser spot size at the transmitting side, D_R is the laser spot size at the receiving side, and L is the distance of the optical communication

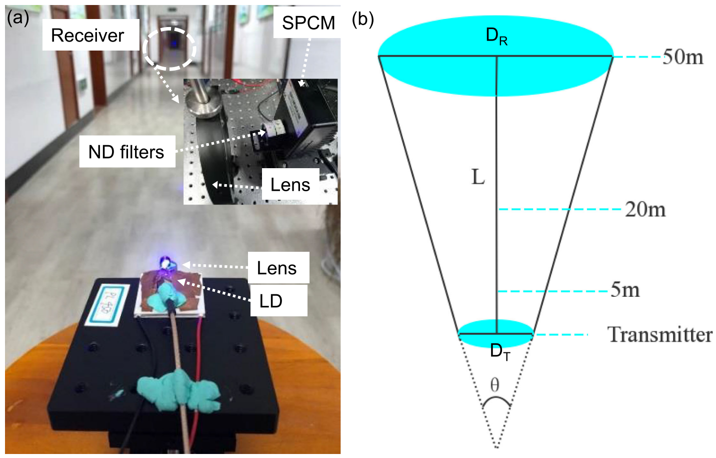

Fig. 7. (a) The pictures of the experimental setup for measuring laser divergence angle in the 50-m corridor, and (b) the schematic diagram of laser divergence.

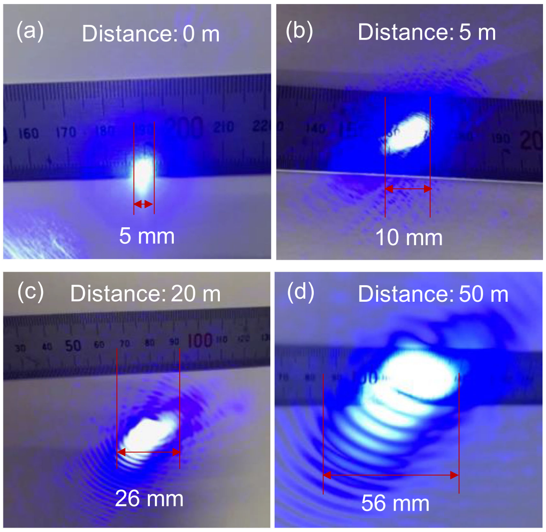

Fig. 8. Receiver laser spot sizes measured at distances of (a) 0 m, (b) 5 m, (c) 20m, and (d) 50 m in the 50-m corridor.

TABLE 3
The laser divergence angles at different distances of free space.

Distance (m)	0	5	20	50
Laser spot size (mm)	5	10	26	56
Laser divergence (mrad)	N/A	1.00	1.05	1.02

system. The laser spot sizes are 5 mm, 10 mm, 26 mm and 56 mm, measured at distances of 0 m, 5 m, 20 m, and 50 m, respectively, as shown in Fig. 8(a)–(d). The corresponding laser divergence angles are shown in Table 3. The average laser divergence angle of free space is about 1.02 mrad. In practical cases, UWOC channels are highly sensitive to particles. As light propagates through UWOC channels, light interacts with particles and gets absorbed or scattered to different directions.

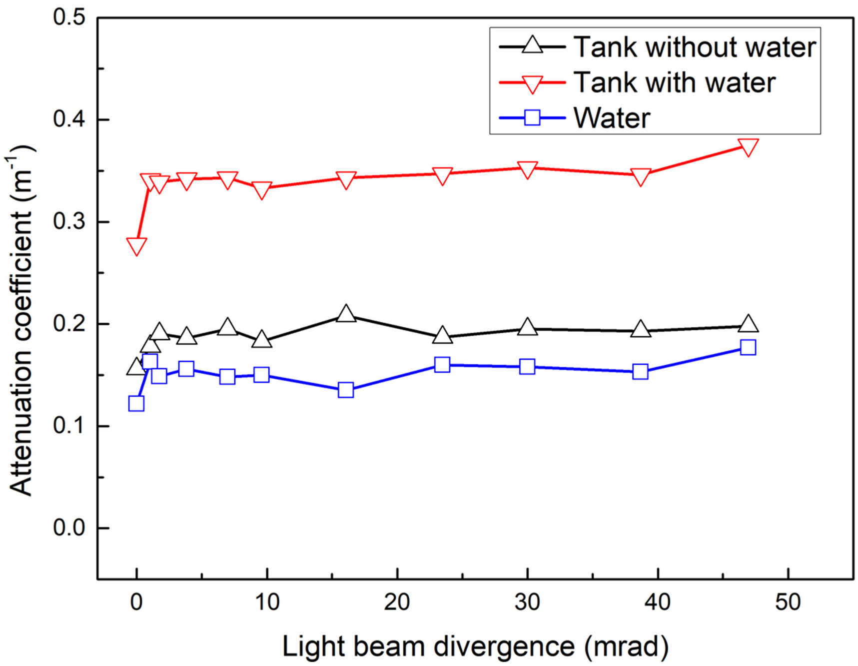

Fig. 9. Attenuation coefficients of water and a 2.3-m tank with and without water at different laser divergence angles.

However, due to the small divergence angle of the laser in water, the impact is small. Based on the analysis of Table 3 and previous studies, the laser divergence angle in pure water will be also around 1.02 mrad. The diameters of laser spots are calculated to be 112 mm and 168 mm at the distances of 100 m and 150 m, respectively. This means that a larger lens can be used to collect light beam, for example, a lens with a diameter of 20 cm.

The attenuation coefficients at different laser divergence angles in a 2.3-m tank with and without water were tested and the attenuation coefficients of water were further calculated according to formula (1), as shown in Fig. 9. At the receiving side, a Fresnel lens was used to focus the light beam. From Fig. 9, the attenuation coefficient is close to the reported value in the literature [27]. And it can be seen that as laser divergence angles increase, the attenuation coefficients also increase slowly. The reason is that the increased divergence angles result in increased optical path lengths, so the loss of optical output power and the attenuation coefficient increase as well. In practical UWOC, greater divergence means a larger laser spot at the receiving side, which would make it harder to collect and detect all the light, resulting in more loss of light power. Therefore, a small divergence angle is beneficial to reduce the attenuation coefficient. The long communication distance of 144 m obtained in this work partly benefits from the small divergence angle. The analyses and tests in this work can be applied to compare the difference between free-space and underwater channels in communication scenarios between facilities such as the underwater vehicles and the airborne terminals or ships.

4. Conclusions

We proposed and experimentally demonstrated a long-distance UWOC system based on a SPAD receiver. A blue LD was used to provide the optical signal, and a high-sensitivity SPAD-based receiver greatly increased the transmission distance. The attenuation coefficient in water is calculated to be 0.12 m^{-1} under the condition that the transmitting and receiving spots are both 5 mm and the divergence angle approaches zero. The maximum estimated distances of 144 m and 117 m with corresponding BERs of 1.89×10^{-3} and 5.31×10^{-4} at data transmission rates of 500 bps and 2 Mbps were acquired in the UWOC system, respectively. We experimentally investigated the minimum divergence angle of ∼1.02 mrad at the distance of 50 m in the free space. A small divergence angle can be achieved by lasers, which also helps achieve long-distance UWOC. Our works are helpful to realize long-distance UWOC in future investigations.

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