ABSTRACT: Underwater wireless optical communication (UWOC) will play an important role in the underwater environment exploration and marine resource development due to its advantages of high data rate and good mobility. However, the significant signal power attenuation in the underwater channel limits the transmission distance of UWOC. Attenuation length (AL) is widely used as an indicator for evaluating the UWOC system’s long-distance transmission capability. At present, Gbps UWOC is limited within 7AL. Using a SiPM based receiver can dramatically increase the AL that UWOC can support. In this paper, a novel UWOC receiver built from an off-the-shelf SiPM has been demonstrated. The finite pulse width and limited bandwidth of SiPM limit the SiPM based UWOC system’s data rate. To boost the system’s data rate, an optimum method to process the SiPM’s signal has therefore been investigated. Based on these methods, the communication capabilities of the SiPM based UWOC have been investigated experimentally. Results show that the SiPM based receiver can support 11.6AL without turbulence and 9.28AL within weak turbulence (scintillation index = 0.0447) at 1 Gbps.

KEY WORDS: DPSK Underwater wireless optical communication (UWOC) Underwater wireless communication

1. Introduction

The underwater environment contains vast natural resources. At present, 95% of the underwater environment hasn’t been explored [1]. Autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs) and underwater wireless sensor networks (UWSNs) are the key techniques to enable underwater exploration [1]. All these techniques require to establish a high-speed and long-distance wireless link to deliver a large volume of gathered data [1]. In the past decades, the underwater wireless communication systems are based on acoustic communication. However, the limited channel bandwidth of acoustic communication (kHz) cannot meet the demand for high capacity communication. UWOC, which has the potential to support multi-Gbps data rate, has attracted significant attention [1–3]. Generally, UWOC encodes information into the light intensity. The main challenge within UWOC is the propagation of light in the water
suffers from severe signal power attenuation. After long-distance underwater transmission, the received optical signal becomes very weak and is difficult to be demodulated. Using high sensitive photodetector to build UWOC receiver can address this challenge [4-7].

At present, the most commonly used high-sensitive detector for UWOC receiver is the avalanche photodiode (APD) [8-14]. Table 1 lists the recent achievements of using APD based receiver for Gbps UWOC. For a given UWOC system, the maximum transmission distance is affected by the turbidity of water. Therefore, for a fair comparison, the attenuation length (AL) is used as the criteria to evaluate the performance of a given UWOC system. Table 1 shows that the maximum AL that has been achieved by APD at Gbps data rate is less than 7 AL. The excess noise generated by the multiplying process within the APD limits the maximum APD gain [15-18]. The excess noise can be avoided by biasing APD over its breakdown voltage which creates a single-photon avalanche diode (SPAD). SPAD is capable of detecting a single photon. When a photon is detected, the SPAD will be inactive for a finite time which is known as the dead time [17]. Using an array of SPADs can mitigate the impact of dead time. The array of SPADs is known as SiPM or Multi-Pixel Photon Counter (MPPC) [17,18].

Research of using SiPM based receiver for UWOC has already begun [19-21]. Table 2 summarizes the recent demonstrations of using SiPM for UWOC. In 2017, IFERMER achieved a 60 m (9AL) UWOC at a data rate of 3Mbps with SensL MicroSB 30035 [19]. In 2018, Zhejiang University (ZJU) achieved 1.875Mbps 46 m UWOC with an MPPC [20]. In 2019, [21] demonstrates a 100Mbps 9AL UWOC using a home-made SiPM. Due to the finite pulse width and limited bandwidth of SiPM, the data rate of the SiPM based UWOC is limited to 100Mbps.

| Year | Paper | Photodiode | Modulation | Tx Optical Power | Distance (m) | AL | Data Rate |
|------|-------|------------|------------|-----------------|--------------|----|-----------|
| 2017 | [19]  | SiPM       | OOK        | 51.3 mW (LED)   | 20           | 1.7| 1.5Gbps   |
| 2017 | [9]   | APD        | OOK        | 10.4 mW (LED)   | 34.5         | 1.49| 2.7Gbps   |
| 2018 | [10]  | APD        | OOK        | 45 mW (LED)     | 10           | 2.55| 40Gbps    |
| 2019 | [11]  | APD        | OOK        | 12.8 mW (LED)   | 25           | 4.84| 5.5Gbps   |
| 2019 | [12]  | APD        | OOK        | 7.25 mW (LED)   | 100          | 3.14| 300Mbps   |
| 2019 | [13]  | APD        | OOK        | 50.2 mW (LED)   | 60           | 3.06| 2.5Gbps   |
| 2020 | [14]  | APD        | OOK        | 10 mW (LED)     | 42           | 4.68| 1.5 Gbps  |

In this paper, an off the shelf SiPM has been used to build a UWOC receiver. An optimum method for improving the SiPM based UWOC data rate has been introduced. Based on this method, 1Gbps SiPM based UWOC has been demonstrated. Results show that the SiPM based receiver can achieve 11.6AL UWOC without turbulence and 9.28AL UWOC with weak turbulence at a data rate of 1Gbps. The AL presented in this paper is the largest result in Gbps UWOC to the best of authors’ knowledge and shows the potential of using SiPM in providing high-speed and long-distance UWOC.

### 2. Method to Increase SiPM’s Data Rate

The significant power attenuation from the underwater channel limits UWOC’s transmission distance. Using a SiPM based receiver can address this challenge. However, the sensitivity of a SiPM based receiver is limited by the non-idealities within SiPM [17]. Results in [17] suggest that a receiver containing a SiPM with a photon detection efficiency (PDE) higher than 14% is more sensitive than APD. Thanks to the continuing improvements in manufacturing processes, SiPM with a PDE higher than 14% is available. In this paper, an off the shelf SiPM SensL J series 30035 which contains an array of 5676 SPADs with a 30%
PDE at 520 nm has been investigated \[22\]. This tested SiPM uses passive quenching scheme and the output signals from all the SPADs within the chip are added together via a common output.

The output signal from SiPM is typically processed by counting pulses \[22\]. The output signals from SiPM are isolated pulses at very low light levels which are shown in Fig. 1(a). Each detected photon generates a single pulse. There is no build-in photon counter within the tested SiPM. The total number of detected photons can therefore be counted by counting pulses in photon counting mode based on photon counting method. Ref. \[23\] introduces two photon-counting methods, namely the peak counting method and the summation method. Peak counting method only uses peak information. This results in photon miss detected when a small pulse is obscured by a large pulse which corresponds to several photons detected simultaneously. The summation method sums the pulse together and is more accurate than the peak counting method \[23\]. With the incident light level increases, more pulses are generated within a given duration. For the tested SiPM, the measured rising time of a single pulse is 520ps and the measured falling time is 1.02 ns. Due to the finite pulse width, pulses become overlapped. After a certain light level, the output pulses become indistinguishable with each other. In this circumstance, photons cannot be accurately counted by counting pulses \[23\]. Figure 1(b) compares the peak counting method and the summation method using the tested SiPM at different light levels. The expected values which correspond to the dashed line are calculated by

\[
\text{Counts} = \frac{\text{PDE} \times L \times A \times T}{E_{\text{ph}}}
\]

where T is the observation time, L is the light intensity in W/m2, A refers to the total area of the SiPM and Eph refers to the single-photon energy. As expected, the summation method is better than the peak counting method. Moreover, the photon counting mode becomes inaccurate when the optical power of the incident light is higher than 0.062 nW and the corresponding maximum detected photon rate \(PR_{\text{max}}\) is \(4.9 \times 10^7\) photons per second.

The maximum OOK data rate in photon counting mode is determined by \(PR_{\text{max}}\) and \(N_p\) which is expressed as \(PR_{\text{max}} / N_p\), where \(N_p\) is the number of detected photons per bit required by the SiPM to achieve a target bit error rate (BER). At a given \(PR_{\text{max}}\), the upper bond of the maximum OOK data rate in photon counting mode can be calculated assuming the SiPM is an ideal photon-counting receiver. Within the ideal photon-counting receiver, Poisson noise is the dominant noise \[17,18\] and no background counts present. Based on Poisson distribution, the number
of detected photons per bit $N_p$ required by an ideal photon-counting receiver to a target BER is given by [23]

$$N_p = -\ln(2 \times BER)$$

According to Eq. (2), 6.2 detected photons per bit are required by an ideal photon-counting receiver to achieve a BER of $10^{-3}$ in the dark. The BER of $10^{-3}$ is below the level at which a standard Forward Error Correction (FEC) code can operate (BER of $3.8 \times 10^{-3}$) [24]. Consequently, the upper bond of the maximum OOK data rate using this tested SiPM in the photon-counting mode is 7.9 Mbps. However, in practice, SiPM suffers from the background noise (dark counts and photon counts generated by ambient light). More number of photons per bit are required to compensate for the background noise. Therefore, the maximum OOK data rate that the photon counting mode can support with this tested SiPM is less than 7.9Mbps. This data rate is far from the Gbps target.

Analogue mode is an alternative operation method recommended by the manufacturer to process SiPM’s output signal [25]. Instead of counting pulses, the analogue mode directly measures the amplitude of SiPM’s output signal. In analogue mode, the frequency response of the SiPM based receiver can be affected by the incident optical power, bias voltage and etc. At the optimum bias voltage (28.5V), the maximum 3dB bandwidth of the tested SiPM is ~107MHz and the corresponding incident optical power is 128nW. The detailed investigation of the influencing factors on SiPM 3 dB bandwidth is beyond the scope of this paper. To release the tested SiPM’s potential for supporting a data rate of Gbps, analogue mode has to be used. Additionally, when the OOK data rate is higher than the bandwidth of the SiPM, inter-symbol interference (ISI) is generated. Hence, equalization (EQ) is required to mitigate the impact of ISI [26,27].

$$Z(k) = \sum_{n=0}^{NF} F_n(k) \cdot S_{out}(k-n) + \sum_{j=1}^{NB} B_j(k) \cdot S_{in}(k-j)$$

where $S_{out}(k)$ refers to received signal and $S_{in}(k)$ is the estimated symbol. To find the optimum filter coefficients $F$ and $B$, the least mean square (LMS) algorithm [26,27] has been applied. Figure 2(d) shows the eye-diagram after DFE. This result suggests that DFE effectively mitigates the impact of ISI.

The blue curve in Fig. 2(a) shows the transmitted signal which has been compressed for better illustration and the blue curve shows the received signal from the tested SiPM at 200Mbps. Cross-correlation has been used to align the received signal with the transmitted signal properly. As expected, the output signal from the SiPM becomes continuous and hence analogue mode has to be used. Figure 2(b) shows the eye diagram of a 200Mbps SiPM based OOK link obtained before EQ. As expected, ISI is significant at 200Mbps. In this paper, decision feedback equalizer (DFE) has been used to reduce ISI. Figure 2(c) shows the schematic of DFE which consists of a transversal feed-forward filter with coefficients $F = [F_1 \ F_2 \ ... \ F_{NF}]$ and a feedback filter with coefficients $B = [B_1 \ B_2 \ ... \ B_{NB}]$. The equalized signal $Z(k)$ is expressed as [26,27]:

![Fig. 2](image.png)

Fig. 2 (a) Received signal from SiPM at 200Mbps (b) Eye diagrams of 200 Mbps OOK link using the tested SiPM before EQ and (c) Schematic of DFE (d) Eye diagram after EQ

Based on the analogue mode and DFE, the sensitivity of the tested SiPM at different data rates
has been measured. Figure 3 shows a diagram of the experimental set-up for sensitivity measurement. A Tektronix AWG5200A arbitrary waveform generator (AWG) is used to convert an OOK modulated pseudorandom binary sequence (PRBS) sequence to the analogue signal. The amplitude of the output signal from the AWG is limited to 500 mV. A Mini-circuit ZHL-1000LN+ amplifier is used to maximize the extinction ratio of the transmitter. Combining with a direct current (DC) bias, the amplified signal is then used to drive a 520 nm pigtailed LD (LP520-SF15). A focal lens is placed before the SiPM based receiver to collect all the received beam spot. A black box is placed over the SiPM based receiver to reduce the ambient light to 1nW. Then a high-resolution oscilloscope (OSC) DSOS254A captures the output signal from the SiPM. After synchronization, the captured signal is low pass filtered and equalized. The equalized signal is then decoded to the binary bits according to the searched optimum decision threshold. The BER is then calculated by comparing the decoded bits with the transmitted bits. If the BER equals to the target BER, then measures the optical power at the receiver. Otherwise, change the transmitted optical power by adjusting the variable optical attenuator (VOA).

The blue curve in Fig. 4 shows the optical power required by the tested SiPM at different data rates to get a target BER of \(10^{-3}\). For SiPM, when no background counts present, the number of signal photons per bit required to get a specific BER, \(N_s\), at different data rates are fixed according to the Poisson statistics \(18\). Therefore, the optical power needed by the SiPM linearly increases with the data rate. When background counts present, to compensate the impact of background counts, \(N_b\) has to be increased with the background counts per bit \(N_b\) \(18\). For a given ambient light level, the background counts rate (background counts per second) is fixed. Therefore, at a given ambient light condition, \(N_b\) decrease with the increase of data rate and hence \(N_s\). Consequently, the increasing rate of the required optical power is getting decreased when the data rate is getting increased. Therefore, the increasing rate of the blue curve is getting reduced with the increase of data rate. Moreover, results in Fig. 4 suggest that the tested SiPM achieves 1Gbps at a BER of \(10^{-3}\) using analogue mode with DFE which only requires a received power of 80nW (-40.9 dBm). The red curve is the estimated result of the achievable AL at a 10 mW transmitted power assuming the channel bandwidth is limited by the tested SiPM and all the power at the receiver plane can be collected. This estimated result suggests that the tested SiPM can support \(\sim 11.6\)AL with a BER of \(10^{-3}\) at 1Gbps.

3.Underwater Channel Characterization

The two assumptions for 1Gbps 11.6AL UWOC estimation has then been validated within a practical UWOC channel. In this paper, the underwater test is performed in a 4 m water tank which has two highly reflective mirrors at both ends. The maximum transmission distance that can be created within this
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The experiment condition is 40 m. Since the long distance transmission capability is interested to the underwater applications, the tested UWOC link is set to 40 m. The overall optical power loss $L_P$ against propagation distance $z$ can be expressed by Beer lambert model which is given by \[^1,2\]

$$L_P(\lambda, z) = e^{-c(\lambda)z} \quad \text{(4)}$$

where $c(\lambda)$ is called the attenuation coefficient which is determined by the turbidity of water. The product of $c(\lambda)$ and $z$ is $AL$. To create a 11.6AL underwater channel within the 40 m link, $c(\lambda)=0.29$ m/s is required which is close to Jerlov II water type ($c(\lambda)=0.303$/m) \[^{28,29}\]. The suspensions of $AL$ ($OH_3$) and $Mg(OH)_2$, Maalox, which has been widely used for varying the turbidity of water \[^7\], is used in the experiment for increasing the turbidity of tap water from $c(\lambda)=0.15$/m to $c(\lambda)=0.29$/m. Figure 5 shows the measured transmittances of the tested water at different propagation distances. This experiment was completed using a 520 nm LD and a power meter (PM130D). The red spots are the measured data, and the blue fitting curve is based on Beer-Lambert model with $c(\lambda)=0.29$/m which suggests that the required turbidity for generating 11.6AL in 40 m has been achieved.

$$\theta = 2\times\arctan\left(0.5\times\frac{d_z-d_i}{l_z-l_i}\right) \quad \text{(5)}$$

Figure 7(b) shows the measured spot size at 8 m and 24 m within tested water are 5 mm and 8 mm correspondingly. The initial spot size is approximately 1 mm. According to Eq. (5), the divergence angle of the tested transmitter is 0.125 mrad. The received spot size $D$ at a distance of $R$ can be calculated as

$$D = 2\times R\times\tan(0.5\times\theta) + d_o \quad \text{(6)}$$

where $d_o$ refers to the initial spot size. Based on Eq.(6), the spot size at 40 m is 6 mm. The tested receiver shown in Fig. 6 uses a 2.5 cm aperture and a 2.5 cm focal lens in front of the SiPM, which limits the field of view (FOV) of the receiver to 30 degrees for reducing the impact of ambient light noise and the multipath. The 6 mm received spot is within the size of aperture and focal lens, and hence can be fully collected. As a result, the assumption of no power loss at the receiving plane for 11.6AL 1 Gbps UWOC estimation is valid using the transmitter and receiver in Fig. 6 within Jerlov II water at a transmission distance of 40 m.

The other assumption is that the tested SiPM limits the channel bandwidth. The channel bandwidth is determined by the underwater channel bandwidth, the transmitter and receiver bandwidth. Multipath generated by scattering determines the underwater channel bandwidth \[^7,30\]. For a given transmitter,
the multipath effect is getting increased with the transmission distance due to the increased scattering events. The receiver ignores the multipath outside the FOV and the aperture. Therefore, the 3 dB bandwidth can be improved with a reduced FOV and a reduced aperture size. The underwater channel bandwidth can be simulated by employing Monte Carlo approach, which has been widely used to analyze the behaviour of the underwater channel \[1,2,7\]. In this approach, the interaction of each photon with the medium are statistically modelled, and the photon propagation paths from the transmitter to the receiver are step by step traced \[1,2\]. Figure 8(a) shows the simulated 3 dB bandwidth of the underwater channel with the coastal ocean water at different transmission distances with different FOVs. In the simulation, the divergence angle of the transmitter is the same as the measured value in Fig. 7, and the aperture size is set to 0.5 m. As expected, the 3 dB bandwidth of the underwater channel reduces with the increase of the transmission distance and reducing the FOV increases the 3 dB bandwidth. Figure 8(b) shows the simulated 3 dB bandwidth of the underwater channel at different aperture sizes when the FOV is fixed at 30 degrees which is the same as the tested receiver shown in Fig. 6. The blue curve represents the 40 m underwater channel with coastal ocean water, and the red curve refers to the 100 m underwater channel with clear ocean water. This simulation result shows that reducing the aperture size improves the 3 dB bandwidth. Additionally, due to the clear water suffers less scattering, the underwater channel with clearer water has a wider 3 dB bandwidth. According to the measured attenuation coefficient \(c(\lambda)\) in Fig. 5, this simulation result suggests that the 3 dB bandwidth of the tested water is smaller than the clear ocean water \(c(\lambda) = 0.15/\text{m}\) and larger than the coastal ocean water \(c(\lambda) = 0.339/\text{m}\) \[1,2\].

The frequency responses of the tested SiPM based UWOC system within the tested underwater channel against different distances have been measured using the transmitter and receiver shown in Fig. 6 and VNA E5063A. In these measurements, the received power over the SiPM is set to 80nW which is consistent with the 1Gbps result in Fig. 4. The measurement results are
shown in Fig. 9. The red curve in Fig. 9 suggests that the bandwidth of this tested SiPM is only 90MHz at this condition. Simulation results in Fig. 8 suggest that the 3dB bandwidth of the underwater channel using the transmitter and receiver shown in Fig. 6 within the coastal water is 170MHz when distance is 40m. Since the turbidity of Jerlov II water is clearer than the coastal water, the 3 dB bandwidth of the tested water is higher than 170 MHz. Moreover, the measured bandwidth of the transmitter is 1GHz. Therefore, the channel bandwidth is limited by the tested SiPM. Consequently, the measured frequency responses in Fig. 9 overlap together. Therefore, the assumption of channel bandwidth is determined by the tested SiPM for the 11.6AL 1 Gbps UWOC estimation is valid using the transmitter and receiver shown in Fig. 6 within the Jerlov II water at a transmission distance of 40 m.

The ultimate performance of this SiPM based UWOC system has been measured without turbulence. Figure 11 shows the measured BERs at 40 m transmission distance with a data rate of 1Gbps at different transmitted powers. This result suggests that this tested system requires 10dBm (10 mW) transmitted power to achieve 11.6AL 1Gbps UWOC at a BER of 10^{-3} which validates the 1Gbps estimation result in Fig. 4.
When turbulence is generated, the received signal fluctuates. Figure 12(b) shows the eye-diagram in the 40 m link with the lowest turbulence that has been generated. The corresponding BER is $8 \times 10^{-3}$ which is over the FEC limit (BER of $3.8 \times 10^{-3}$). With turbulence, reducing the transmission distance can improve the received optical power and hence improving the BER performance of this SiPM based UWOC system. Figure 13 shows the measured BERs at 32 m transmission distance within the four turbulence levels. Based on the method proposed in [31,32], the corresponding scintillation indexes (SI) of the generated turbulence have been measured, which are listed in Table 3. The inset histogram in Fig. 13 illustrates the fluctuation of the received power at SI equals to 0.0447, and the red curve is the lognormal model for estimating the power distribution of turbulence [31,32]. The inset eye-diagram in Fig. 13 shows that eye-opening has been achieved in the turbulence with SI equal to 0.0447. The corresponding BER is $2 \times 10^{-3}$ which bellow the FEC limit. Therefore, this tested SiPM based UWOC system has achieved 32 m (9.28AL) UWOC in the weak turbulence with SI equal to 0.0447.

### 5. Conclusion

In this paper, an off the shelf SiPM has been used to build a novel UWOC receiver to support large AL and high-speed UWOC. SiPM’s manufacturer has introduced two output signal operation modes, photon counting mode and analogue mode. Results show that the photon counting mode within the tested SiPM will be inaccurate when the OOK data rate is higher than 7.8Mbps. Therefore, at high data rates, the analogue mode is the optimum mode. The experimental result shows that ISI is significant at high data rate, and the impact of ISI can be effectively mitigated with DFE.
Using analogue mode and DFE, the sensitivity of the tested SiPM based receiver has been measured. Based on the measured sensitivity, it has been estimated that the SiPM based receiver can support 11.6AL 1Gbps UWOC assuming all the power can be fully collected at the receiving plane, and SiPM limits the channel bandwidth. These two assumptions have been validated within Jerlov II water at a transmission distance of 40 m through Monte Carlo simulation and measurements. The estimated result is finally verified through a 1 Gbps 40 m UWOC test with the tested SiPM in a 4 m water tank. The measurement result shows that 1Gbps 11.6AL UWOC has been achieved. To the best of the author knowledge, this is the largest AL has been achieved in Gbps UWOC. Moreover, in practice, the turbulence within the underwater channel degrades the system’s performance. The measurement result shows that this SiPM based UWOC system achieves a 1Gbps 32 m (9.28AL) UWOC within weak turbulence (SI=0.0447). These results suggest that the SiPM based receiver offers a promising future for realizing high-speed and long-distance UWOC.

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Communications,” IEEE J. Oceanic Eng. 38(4), 730–742 (2013).

[8] C. Shen, Y. Guo, H. M. Oubei, T. K. Ng, G. Liu, K.-H. Park, K.-T. Ho, M.-S. Alouini, and B. S. Ooi, “20-meter underwater wireless optical communication link with 1.5 Gbps data rate,” Opt. Express 24(22), 25502–25509 (2016).

[9] X. Liu, S. Yi, X. Zhou, Z. Fang, Z.-J. Qiu, L. Hu, C. Cong, L. Zheng, R. Liu, and P. Tian, “34.5 m underwater optical wireless communication with 2.70 Gbps data rate based on a green laser diode with NRZ-OOK modulation,” Opt. Express 25(22), 27937–27947 (2017).

[10] Y. Huang, C. Tsai, Y. Chi, D. Huang, and G. Lin, “Filtered multicarrier OFDM encoding on blue laser diode for 14.8-Gbps seawater transmission,” J. Lightwave Technol. 36(9), 1739–1745 (2018).

[11] C. Fei, X. Hong, G. Zhang, J. Du, Y. Wang, and S. He, “Improving the Performance of Long Reach UOWC with Multiband DFT-Spread DMT,” IEEE Photonics Technol. Lett. 31(16), 1315–1318 (2019).

[12] J. Wang, C. Lu, S. Li, and Z. Xu, “100 m/500 Mbps underwater optical wireless communication using an NRZ-OOK modulated 520 nm laser diode,” Opt. Express 27(9), 12171–12181 (2019).

[13] C. Lu, J. Wang, S. Li, and Z. Xu, “60 m/2.5 Gbps underwater optical wireless communication with NRZ-OOK modulation and digital equalization,” in Proc. of Conference on Lasers and Electro-Optics (CLEO) (2019).

[14] W. Lyu, M. Zhao, X. Chen, X. Yang Y. Qiu, Z. Tong, and J. Xu, “Experimental demonstration of an underwater wireless optical communication employing spread spectrum technology,” Opt. Express 28(7), 10027–10038 (2020).

[15] D. Chitnis and S. Collins, “A SPAD-Based Photon Detecting System for Optical Communications,” J. Lightwave Technol. 32(10), 2028–2034 (2014).

[16] E. Fisher, I. Underwood, and R. Henderson, “A Reconfigurable Single-Photon-Counting Integrating Receiver for Optical Communications,” IEEE J. Solid-State Circuits 48(7), 1638–1650 (2013).

[17] L. Zhang, H. Chun, Z. Ahmed, G. Faulkner, D. O’ Brien, and S. Collins, “The Future Prospects for SiPM-Based Receivers for Visible Light Communications,” J. Lightwave Technol. 37(17), 4367–4374 (2019).

[18] L. Zhang, D. Chitnis, H. Chun, S. Rajbhandari, G. Faulkner, D. O’ Brien, and S. Collins, “A Comparison of APD- and SPAD-Based Receivers for Visible Light Communications,” J. Lightwave Technol. 36(12), 2435–2442 (2018).

[19] P. Leon, F. Roland, L. Brignone, J. Opderbecke, J. Greer, M. A. Khalighi, T. Hamza, S. Bourennane, and M. Bigand, “A new underwater optical modem based on highly sensitive Silicon Photomultipliers,” OCEANS 2017 – Aberdeen, Aberdeen, 1–6 (2017).

[20] J. Shen, J. Wang, X. Chen, C. Zhang, M. Kong, Z. Tong, and J. Xu, “Towards power-efficient long-reach underwater wireless optical
communication using a multi-pixel photon counter,” Opt. Express 26(18), 23565–23571 (2018).

[21] J. F. C. Carreira, G. N. Arvanitakis, A. D. Griffiths, J. J. D. McKendry, E. Xie, J. Kosman, R. K. Henderson, E. Gu, and M. D. Dawson, “Underwater Wireless Optical Communications at 100 Mb/s using Integrated Dual-Color Micro-LEDs,” 2019 IEEE Photonics Conference (IPC), San Antonio, TX, USA, 1–2 (2019).

[22] http://sensl.com/downloads/ds/DS-MicroJseries.pdf. [Accessed: 05Jan-2018].

[23] L. Zhang, H. Chun, G. Faulkner, D. O’ Brien, and S. Collins, “Efficient pulse amplitude modulation for SPAD-based receivers,” 2018 Global LIFI Congress (GLC), Paris, 1–5 (2018).

[24] ITU-T, “Forward error correction for high bit-rate DWDM submarine systems,” (ITU, 2004), http://www.itu.int/rec/T-REC-G.975.1-200409-I/en

[25] “Introduction to the Silicon Photomultiplier (SiPM),” [Online]. Available: http://sensl.com/documentation/

[26] Govind P. Agrawal, “Fiber Optic Communication Systems,” (John Wiley & Sons. Inc, 1997).

[27] J. G. Proakis, “Digital Communications,” (McGraw-Hill, 2007).

[28] M. Solonenko and C. Mobley, “Inherent optical properties of Jerlov water types,” Appl. Opt. 54(17), 5392–5401 (2015).

[29] S. Hu, L. Mi, T. Zhou, and W. Chen, “35. 88 attenuation lengths and 3. 32 bits/photon underwater optical wireless communication based on photon-counting receiver with 256-PPM,” Opt. Express 26 (17), 21685–21699 (2018).

[30] C. Gabriel, M. Khalighi, S. Burennane, P. Leon, and V. Rigaud, “Monte-Carlo-Based Channel Characterization for Underwater Optical Communication Systems,” J. Opt. Commun. Netw. 5(1), 1–12 (2013).

[31] Z. Vali, A. Gholami, Z. Ghassemlooy, M. Omoomi, and D. Michelson, “Experimental study of the turbulence effect on underwater optical wireless communications,” Appl. Opt. 57(28), 8314–8319 (2018).

[32] Y. Weng, Y. Guo, O. Alkhazragi, T. K. Ng, J. Guo, and B. S. Ooi, “Impact of Turbulent-Flow-Induced Scintillation on Deep-Ocean Wireless Optical Communication,” J. Lightwave Technol. 37(19), 5083–5090 (2019).
使用基于硅光电倍增器(SiPM)的接收机实现了超过10衰减长度的每秒千兆比特水下无线通信

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摘  要:
水下无线光通信(UWOC)以其数据传输速率高、移动性好等优点,将在水下环境探测和海洋资源开发中发挥重要作用。然而,水下信道中信号功率的严重衰减限制了UWOC的传输距离。衰减长度(AL)是一项被广泛用于衡量UWOC系统长距离传输能力的重要指标。目前,Gbps级的UWOC被限制在7AL以内。使用基于SiPM的接收机可以显著提高UWOC可支持的AL。在这篇论文中,该猜想通过一个由商用SiPM探测器构建的新型UWOC接收机进行了证明。SiPM有限的脉冲宽度和带宽限制了基于SiPM的UWOC系统的数据传输速率。为了提高系统的数据传输速率,本文研究了处理SiPM信号的最佳方法。基于这些方法,对基于SiPM的UWOC的通信性能进行了实验研究。结果表明,基于SiPM的接收机在1Gbps速率无湍流的情况下可以支持11.6AL,在弱湍流(闪烁指数=0.0447)下可以支持9.28AL。