Adaptive Receiver Control for Reliable High-Speed Underwater Wireless Optical Communication With Photomultiplier Tube Receiver

Jie Ning, Guanjun Gao, Jialiang Zhang, He Peng, and Yonggang Guo

Abstract—**Photomultiplier tube (PMT) receiver is a promising solution for long-distance underwater wireless optical communication (UWOC) due to its characteristics of high gain, low noise, and large receiver area. However, the complex underwater environment leads to the dynamic change of the received optical intensity and impacts the stability and reliability of UWOC system using PMT. In this work, the bandwidth limitation and performance degradation of UWOC system caused by PMT saturation is experimentally observed and characterized for various optical intensity and PMT gain. A low-cost, high-integrated, and small-volume receiver control system and relevant adaptive control strategy are proposed to improve the stability and reliability of UWOC system by dynamically adjusting the received optical power and PMT gain according to the detected optical signal. The experiment results show that the dynamic range of UWOC received optical power can be extended to 68 dB (−63 dBm∼5 dBm) for 100 Mbit/s OOK modulation based UWOC system.**

Index Terms—**Underwater wireless optical communication (UWOC), photomultiplier tube (PMT), adaptive receiver control.**

I. Introduction

Underwater wireless communication plays an important role in ocean exploration, scientific ocean observation, and ocean engineering. Compared to underwater acoustic communication, underwater optical wireless communication (UWOC) is featured for its wide communication bandwidth, high transmission bit rate, low latency, and high efficiency, and thus attracts increasing attention and interest for high-speed underwater communication especially. Recently, many great efforts have been devoted to realizing high-speed and long-distance UWOC. In laboratory conditions with precise light path alignment, a light-emitting diode (LED) based underwater visible light communication system with multi-tone modulation achieve 2.23Gbit/s real-time signal transmission over 1.2m underwater link [1]. a 30Gbit/s four-level pulse amplitude modulation (PAM4) underwater wireless laser transmission has been demonstrated over 12.5-m piped underwater channel and 2.5-m high-turbidity harbor underwater channel using avalanche photodiode (APD) [2]. Successful transmission of 500 Mbit/s NRZ-OOK signal over 100-meter distances has also been demonstrated in laboratory conditions with very small transceiver aperture, accurate light alignment using APD [3]. For further increase the transmission distance especially for a deep undersea environment without accurate light alignment conditions, detectors with higher sensitivity and larger detection aperture such as photomultiplier tube (PMT) and silicon photo-multiplier (SiPM) have been demonstrated. For instance, researchers from Woods Hole Oceanographic Institution demonstrate LED-based diffuse undersea UWOC protype over distances of 100-200 meters in a deep-sea trial in 2008 [4]. Following that, a commercial UWOC equipment BlueComm 200 has been available to provide subsea wireless optical communications up to 10 Mbps at ranges up to 150 meters [5]. Moreover, in another deep-sea trial, researchers from JAMSTEC demonstrate 20Mbps bi-direction UWOC transmission over 120 m at 700m depth [6]. In addition to the long-distance and deep-sea UWOC demonstration using a PMT-based receiver, a SiPM detector-based UWOC protype has also been demonstrated through a shallow sea experiment in 2017 by IFREMER (French Research Institute for Exploitation of the Sea) [7]. In addition to increasing the transmission distance and bitrate, the reliability of UWOC also becomes a very important issue for real undersea applications, where the optical power at the receiver changes dynamically according to the change of communication distance, channel attenuation, air bubbles, underwater turbulence, and relative movement of underwater vehicles et al [8]–[10]. These effects make the dynamic change of the received light intensity and impact the communication reliability through several aspects. First, the overexposure of PMT under a bright received light or environmental ambient background causes temporal PMT performance deterioration or even unrecoverable damage to the photocathode of PMT, which causes the gain of PMT to drop substantially and the output becomes very noisy [11], [12]. For this reason, the utilization of PMT often requires careful handling and avoids excessive

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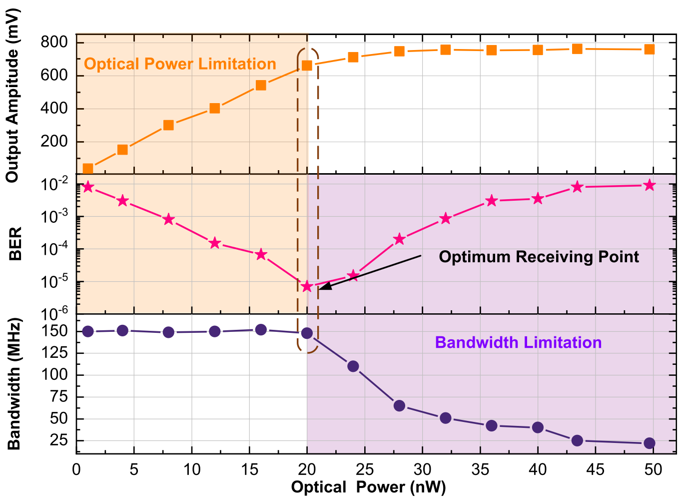

Fig. 1. The squares, stars, and rounds were measured output amplitude of the signal, bit error rate (BER), and 3dB bandwidth at different light power, respectively. The gain of PMT was fixed at $3x10^5$.

fluctuation of incident light intensity. Second, as a very sensitive detector, the PMT may experience signal distortion if working at saturation or nonlinear region [13]. Third, the frequent power fluctuations make the PMT output change dynamically, which impacts the accurate digital recovery and signal level decision. Therefore, achieving adaptive optical power control and PMT output adjustment is not only meaningful to protect the PMT from overexposure due to large power fluctuations, but also of great importance to improve the reliability of UWOC system.

Until now, the nonlinear effect caused by device limitation, which is an important factor limiting the high-speed UWOC system, is widely concerned by researchers [14], [15]. However, there are few studies focusing on investigating the nonlinear effect of high-sensitive UWOC system due to PMT saturation, as well as the adaptive control method under dynamic conditions. In the laboratory environment, neutral density filters are often used as variable optical attenuators before photodetector [16], [17]. However, this method mostly uses motor driving or even manual adjustment the of filtering position to adjust the optical power, which limits its practical use in a real undersea environment due to its large size, coarse tuning step, and low accuracy, and also slow tuning speed. The concept of a smart UWOC system with multiple transmitter and receiver arrays has also been introduced to enhance the adaptivity of UWOC transceivers, but it does not consider the adaptive power control at the receiver [18], [19]. For realizing automatic detection adjustment, two kinds of automatic gain control methods of PMT are presented, which show the 40 dB dynamic range of the receiver [20]. Although the tolerance of received optical power can be increased by automatic gain control, its dynamic range is still limited and the PMT performance deterioration caused by excessive power exposure cannot be avoided.

In this paper, we first analyze and characterize the influence of optical power and the gain of PMT on the system bandwidth and the UWOC performance using a high-sensitive PMT receiver. Experimental results show that the reduction of PMT bandwidth at saturation or nonlinear region can cause signal distortion and limit the system performance. Then, an adaptive control system based on liquid crystal light valve (LCLV) and gain of PMT control technology is proposed, which has the advantages of low cost, high integration, small volume, and is suitable for a reliable UWOC system. On this basis, we propose a joint dynamic control strategy based on LCLV and PMT gain, which is used to realize the adaptive control of the received signal. Experimental results prove that by utilizing the adaptive receiver control method, a wide dynamic range of PMT based underwater receivers can be extended to 68 dB (−63 dBm∼5 dBm) for 100 Mbit/s OOK modulation, which is largest to the best of our knowledge.

II. Principle and Control Strategy of the Adaptive Control System

A. Signal Characterization of UWOC System With PMT Receiver

For the UWOC system with a PMT receiver, the performance of the received signal depends on the incident signal power and the internal noise of the system, which can be described by the signal-to-noise ratio (SNR) of the output signal. The SNR can be expressed as [12]:

$$SNR = \frac{I_k}{\sqrt{(2eBN_F)\left(I_k+2I_d+N_A^2\right)}} \tag{1}$$

where I_k is cathode current of PMT, e is the electron charge, $e = 1.602 \times 10^{-19}C$, B is the bandwidth of the system, N_F is the noise figure of PMT, and I_d , N_A are the dark photocurrent and the input noise current of the operational amplifier respectively. From the analysis of formula (1), the SNR cannot be improved by increasing the internal gain of PMT. But it can be effectively improved by increasing the power of incident light of signal, i.e., increasing the cathode current of PMT. However, when the signal optical power increases to a certain level, the output signal of PMT will be distorted due to the influence of the space charge effect, which leads to the limited bandwidth of the receiving system. With the increase of signal optical power, the effect of bandwidth limitation will be more obvious, which will lead to the deterioration of system performance.

In order to analyze the nonlinear effect of PMT based UWOC receiver, an experimental system, which is elaborated in Section III, is used to measure the amplitude, bandwidth, and bit error rate (BER) of the received signal under different incident light power and the results are shown in Fig. 1, The performance of the received signal is first limited by the input optical power. Due to the influence of noise, increasing incident optical power obviously results in an increased detection SNR, and hence, an efficient BER performance. When the input optical power intensity is too large, the output signal of PMT working in the saturation region begins to appear distorted, which leads to the decrease of system bandwidth. At this time, the received signal performance will be degraded by the bandwidth limitation. Overall, the performance of the received signal is affected by optical power and system bandwidth. Therefore, the optimum received signal is obtained at the position of maximum signal optical power when the bandwidth is not reduced.

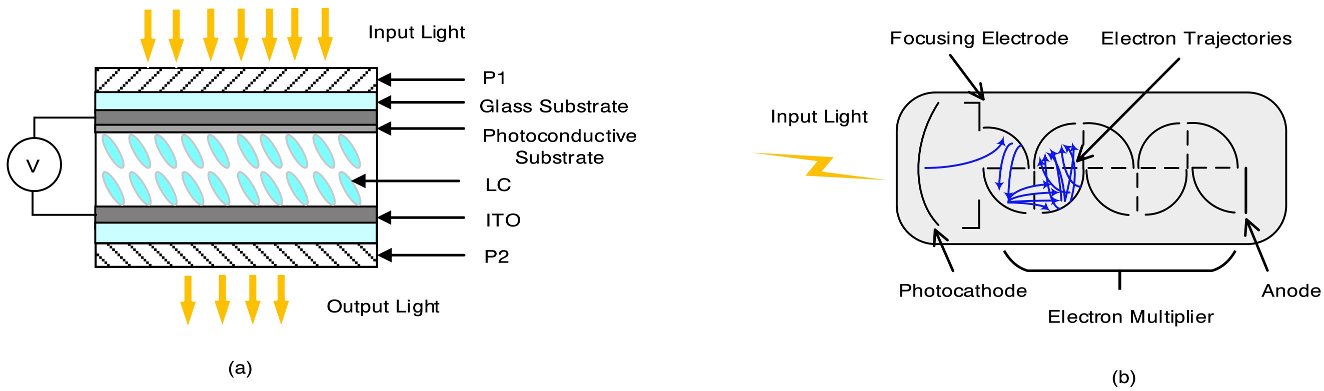

Fig. 2. (a) Construction of LCLV. P1, P2-polarizer, LC-liquid crystal, ITO- transparent conductive layer (b) Construction of PMT.

B. Principle of Adaptive Control System

The adaptive control system combines an integrated control of LCLV and PMT gain control, making it possible to adaptive adjustment of the detected signal in a large dynamic range. LCLV is a kind of spatial light modulator based on the electro-optic birefringent effect of liquid crystal. The construction of LCLV is illustrated in Fig. 2(a). To ensure the light transmission of LCLV in the initial state, both P1 and P2 are polarizers with the same vertical polarization direction. In the LCLV the liquid crystal (LC) layer and a photoconductive substrate are sandwiched between indium tin oxide (ITO) coated glass substrates. When an external voltage is applied between the ITO electrodes, the alignment of liquid crystal molecules will be deflected under the action of an external electric field. If a light beam passes through the LCLV, because of the large birefringence of the LC, the output light beam acquires a great phase shift, which makes the light transmittance of LCLV change. The transmitted light intensity I_{out} of the LCLV can be expressed as [21]:

$$I_{out} = I_0 \sin^2 \alpha \sin^2 \frac{d\Delta n(v)\pi}{\lambda} \tag{2}$$

where I_0 is the intensity of the incident beam, α represents the angle between the optical axis of the LC molecules and the X-axis, d is the thickness of the liquid crystal. The Δn is the equivalent refractive index difference of LC, which is affected by the applied voltage v. For a specific laser wavelength λ, if the appropriate control voltage range is selected, the transmittance of the LCLV can be continuously changed between 0% $\sim$ 100% to achieve continuous light intensity attenuation in a large dynamic range.

PMT is a kind of vacuum photoemission device, which is based on the theory of photoelectron emission effect, secondary electron emission effect, and electron optics. As shown in Fig. 2(b), the generation and amplification of photocurrent in PMT are determined by photocathode, electron multiplication stage, and anode. The output current I_A is expressed as [22]:

$$I_A = I_0 \cdot S_K \cdot G \tag{3}$$

where S_K is the cathode radiation sensitivity and the gain of PMT G depends on the operating voltage v loaded on the gain multiplier, which can be expressed as:

$$G = A \cdot v^{kn} \tag{4}$$

where A is a constant, k is a parameter determined by the structure and material of the multiplier stage, and its typical value is $0.7 \sim 0.8$, and n is the multiplier series of PMT. Therefore, by controlling the working voltage of the PMT multiplier electrode, the PMT gain can be precisely controlled, and then the final PMT output signal level can be adjusted which helps to improve the receiver sensitivity for weak UWOC signals.

The whole adaptive control system consists of three units: signal control unit, signal processing unit, and data processing unit, as shown in Fig. 3. The signal light through the LCLV is accepted by a PMT module and converted into a negative current signal. Then a trans-impedance amplifier (TIA) converted current signals to a voltage signal and the signal is amplified secondary by an inverting amplifier (INV AMP) and converted to a positive signal for relaxing receive. The processed signal is used to recover the data from digital signal processing (DSP), and the other one is fed into a data acquisition unit based on a microcontroller unit (MCU) through an A/D converter. The MCU analyzes and calculates the collected signal through the internal algorithm strategy, obtains the control parameters, and sends out control commands to the outside. After D/A conversion, the control voltage signals are respectively transmitted to LCLV driving control unit and gain control unit to realize the LCLV and gain of PMT adaptive adjustment.

C. Adaptive Control Strategy

The purpose of the adaptive control strategy is to calculate the target control parameters according to the current signal receiving state, so as to achieve fast and accurate detection control. For this reason, for achieving optimum detection for a given optical power and signal bandwidth, both the received optical power and PMT gain should be set at an appropriate value for achieving optimum SNR, power sensitivity while avoiding signal distortion.

Through the analysis of the characteristics of the received signal (see Section II-A), we can establish the relationship between the optimal output amplitude of the signal and the bandwidth, and the target amplitude can be calculated according

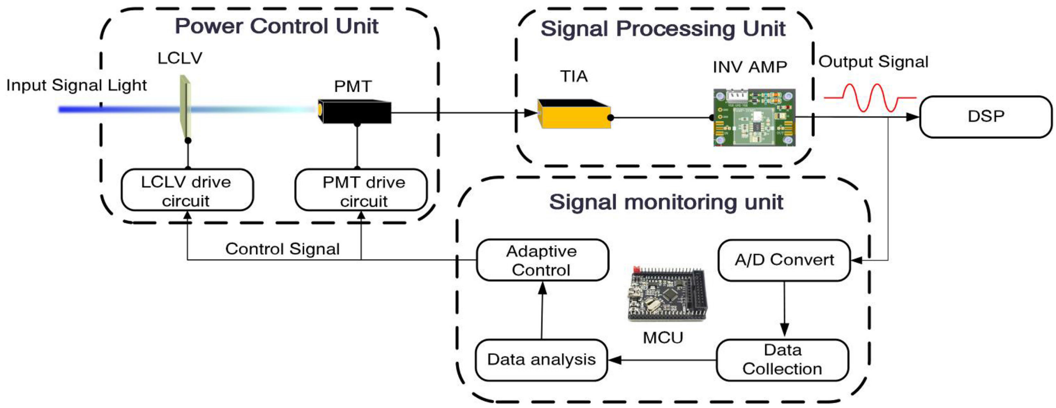

Fig. 3. Construction of AOPC system. The following abbreviation is used: TIA – trans-impedance amplifier, INV AMP – inverting amplifier, MCU- microcontroller unit.

to the current signal transmission rate. Considering the PMT bandwidth limitation caused by excessive optical power, the target signal output amplitude P_s avoids performance degradation can be expressed as:

$$P_s = f(B) \tag{5}$$

where B is signal transmission bandwidth. In the UWOC system, the modulated light signal from the transmitter is adjusted in the adaptive control system to form the final received signal. The received signal output amplitude can be expressed as:

$$P = I_0 \cdot f_T(v_{LCLV}) \cdot f_G(v_{PMT}) \cdot G_{TIA} \cdot G_{INV} \tag{6}$$

where G_{TIA} and G_{INV} is the gain multiple of TIA and INV AMP, respectively. The $f_T(v_{LCLV})$ is the light transmittance of LCLV as a function of control voltage v_{LCLV} and $f_G(v_{PMT})$ is the gain of PMT as a function of control voltage v_{PMT}. Therefore, by jointly control the voltage of LCLV and PMT gain, the analytical expression of the optimal output can be expressed as

$$T \cdot G = \frac{f(B)}{I_0 \cdot G_{TIA} \cdot G_{INV}} \tag{7}$$

where T is the transmittance of LCLV and G is the gain of PMT. The exact control method of both transmittances of LCLV and gain of PMT can be obtained as the following procedure.

First, set the current T as the maximum state $T = T_{max}$, where G is the minimum state $G = G_{min}$. Set the target control parameter as S.

1) If $T \cdot G = S$, the receiving state is in the best state, and the control parameters remain stable.
2) If $T \cdot G < S$, it indicates that the current incident light signal power is weak. At this time T is the maximum value and cannot continue to increase. Therefore, the current gain of PMT should be increased, and the control parameter is $T = T_{max}$, $G = S/T$.
3) If $T \cdot G < S$, it indicates that the current incident light signal power is strong, at this time, G is the minimum value and cannot continue to reduce. Therefore, the transmittance of LCLV should be reduced and the parameters should be adjusted to $G = G_{min}$, $T = S/G$.

By adopting the above dynamic control strategy, the control parameters of both LCLV and PMT gain can be calculated directly. Compared with the control strategy based on error feedback, which needs to adjust and control many times to achieve the stability of the received signal according to the error value, this method is more accurate and stable. By setting the exact control voltage for LCLV and PMT gain according to the parameters, stable and optimal signal reception can be achieved, and the reliability of UWOC system can be improved.

III. Experimental Setup

The schematic diagram and experimental setup of UWOC system based on the adaptive control system are depicted in Fig. 4(a) and Fig. 4(b), respectively. At the transmitter, a non-return-to-zero on-off keying (NRZ-OOK) format electrical signal was generated by an AWG (Agilent m8190a, 4GHz bandwidth, 40GSa/s, 14bit), output by CH1 port. The output signal was adjusted by an amplifier (minicircuits ZHL-6A-S+, 500M bandwidth) and combined with 200mA direct currents by bias tees (minicircuits ZFBT-4R2GW,500M bandwidth). The transmitter light source was a 450nm blue laser diode (LD) with a maximum output power of 80mw. The fluctuating optical signal intensity was controlled by a variable neutral density (ND) filter placed just after the LD. The light was transported in a UWOC channel of 2m long with clean tapped water inside a water tank. A dark box is covered in the water tank and the receiver, so as to effectively avoid the interference of ambient light on the experiment. At the receiver side, Since the PMT can detect the weak optical signal exceeds the minimum detection power that the optical power meter can detect. In order to ensure that the intensity of the optical signal can be accurately collected, a beam splitter divides the optical signal into two beams in a ratio of 1:10 weak different beams. One of the strong beams is received by an optical power meter (Thorlabs PM200, 1nW$\sim$5mW) to measure the current received light intensity, and the weak beam was detected by the adaptive control system and recorded by a digital storage oscilloscope with 40 GHz bandwidth and the system bandwidth was measured by a vector analyzer (Tektronix TTR500, 6GHz bandwidth).

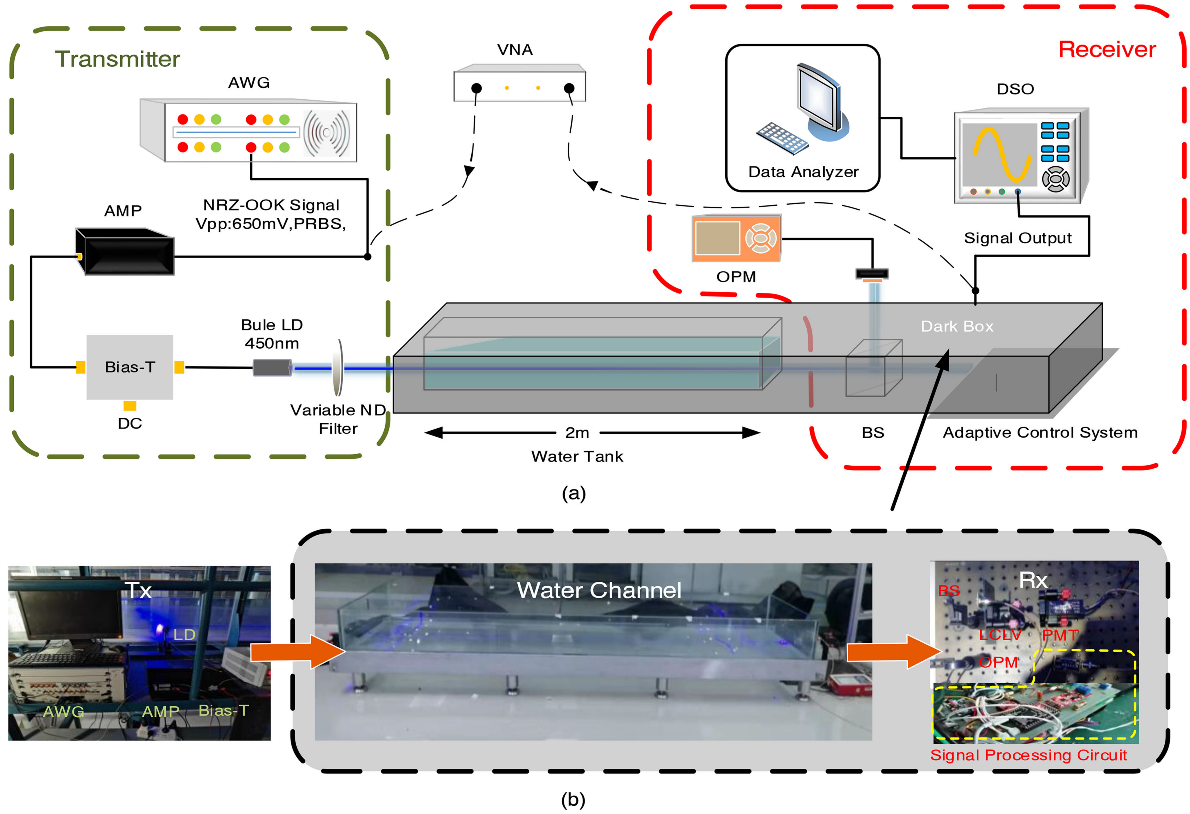

Fig. 4. The Schematic diagram of UWOC system with adaptive control. The following abbreviation is used: OPM – optical power meter, DSO – digital storage oscilloscope, AWG - arbitrary waveform generator, AMP - amplifier, BS - beam splitting, VNA-vector analyzer. (b) Experimental setup of UWOC system with adaptive control.

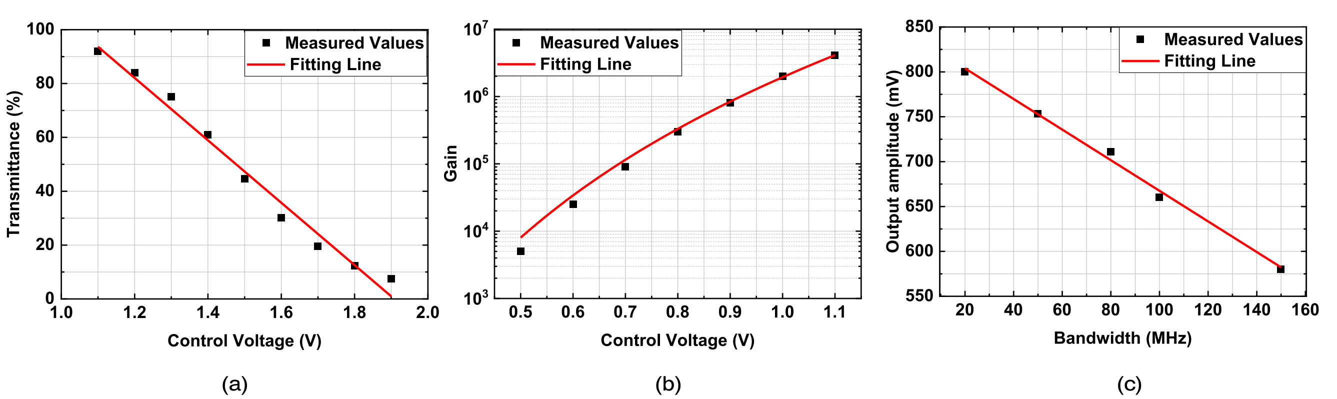

Fig. 5. (a) light transmittance curve of LCLV under different control voltage. (b) Gain curve of PMT H10720-210 under different control voltages. (c) Relationship between bandwidth and optimal signal output amplitude.

IV. Results

In order to realize the adaptive control of the signal, it is necessary to measure the control parameters of the system. By changing the driving voltage at both ends of LCLV, we measured the optical power before and after passing through LCLV, and realize the measurement of light transmittance of LCLV. The measured values are shown in Fig. 5(a) and a linear fitting is conducted. When the control voltage is adjusted in the range of 1.1V $\sim$ 1.9V, the relative light transmittance of LCLV can change continuously in the range of 10% $\sim$ 90%. Because the relationship between gain and control voltage of different types of PMT is different. We selected PMT H10720-210 (Hamamatsu Corporation, Japan), whose working voltage can be regulated by an external control voltage. Fig. 5(b) shows the measurement results of control voltage and gain of PMT. When the control voltage of PMT is adjusted in the range of 0.5-1.1V, the gain of PMT can be continuously adjusted in the range of $5x10^3 \sim 4x10^6$. Finally, Fig. 5(c) shows the best-received signal amplitude when the measured system bandwidth varies from 20$\sim$150MHz.

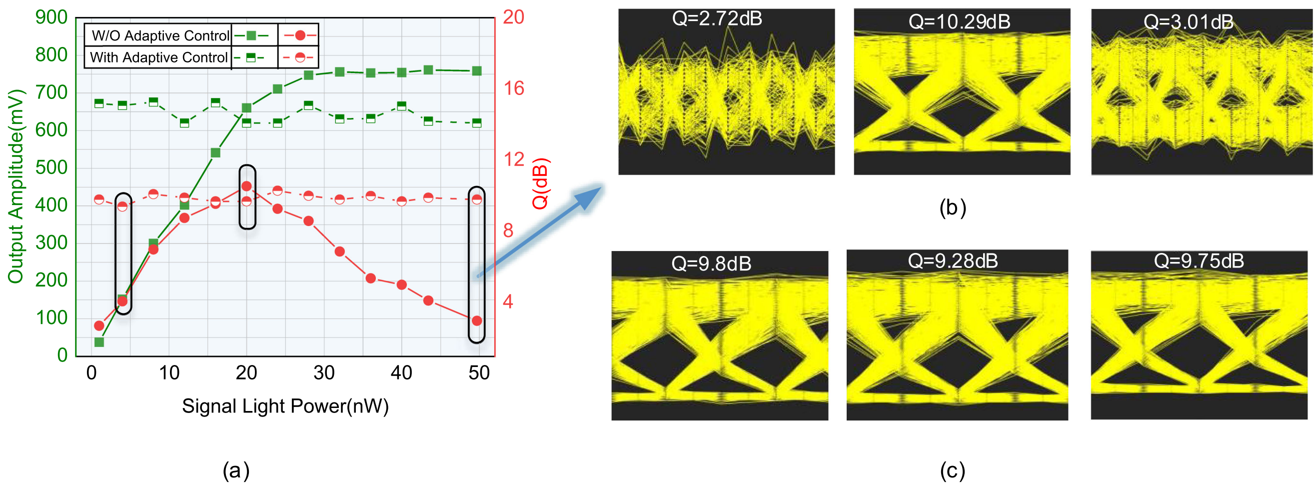

Fig. 6. (a) Signal output amplitude and SNR versus light power. (b) The measured eye diagrams of OOK modulation without adaptive control. (c) The measured eye diagrams of OOK modulation under adaptive control.

To verify the performances of the adaptive control system on the received signal, the PMT was illuminated by a continuously varying light signal. Fig. 6(a) shows the measured output amplitude and Q factor versus the light power illuminated on the PMT. In the absence of adaptive control, the output of the received signal increases rapidly to 750 mV with the increase of the signal optical power, and the received signal reaches saturation and does not continue to increase. At the same time, the Q factor first shows the same increasing trend as the output amplitude. When the signal enters the saturation region, the Q factor decreases rapidly because the output signal is affected by the saturation effect. The maximum Q factor is obtained when the incident light power is 20nW, and the signal amplitude is 650mV. Therefore, we select the output amplitude when the maximum Q factor as the target control parameter. Under the condition of adaptive control, the output amplitude keeps a small range fluctuation near the target value, and the Q factor remains above 9dB. Fig. 6(b) and Fig. 6(c) respectively compare the eye diagrams of the received signals without adaptive control and with adaptive control. When the incident light power is weak or too strong, the eye-opening become smaller due to the influence of system noise and bandwidth limitation. The received signal after adaptive control is less affected, and the eye keeps a good opening.

In order to further verify the performance of the adaptive control system, we tested the dynamic receiving range limit of the system. In the experiment, the AWG produced a standard NRZ-OOK of 100Mbit/s to drive the transmitter module generates a modulated optical signal. We have presented in Fig. 7 plots of BER versus optical power. With the increase of the optical power, the measured BER value shows a trend of gradually decreasing and then increases rapidly due to the bandwidth limitation, which was expected. Under the BER threshold of $3.8\text{x}10^{-3}$ assuming 7% FEC overhead, the achieved dynamic range is about 7.2dB (-59.3dBm ∼ -52.1dBm) for the maximum PMT gain control voltage and 19.1dB (-44dBm ∼ -24.9dBm) for the minimum PMT gain control voltage. the attainable maximum dynamic range for a given target BER decreases with an increasing gain of

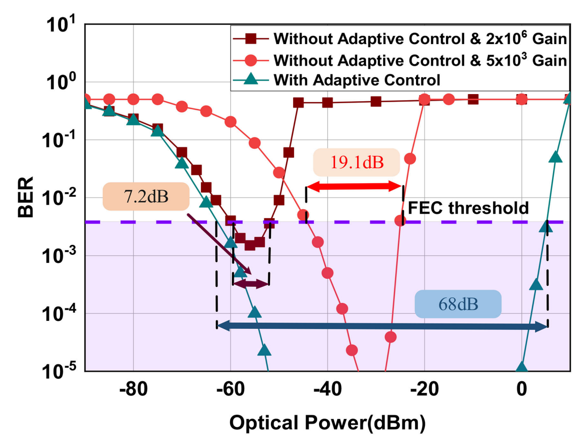

Fig. 7. BER versus optical power for the PMT (H10720-210) receiver with different control method. NRZ-OOK with data rates is 100 Mbit/s.

PMT. Under the same conditions, the dynamic range of adaptive control system by the LCLV and gain control strategy expands 68dB (-63dBm ∼ 5dBm).

Due to different water quality environments, the intensity of light attenuation is different. We consider the water under the current experimental environment as the standard. The attenuation length (AL) is used instead of transmission distance as an indicator of system performance. The attenuation coefficient of water is 0.2/m, which is measured with an optical power meter. We use the measured attenuation coefficient and the optical power range in Fig. 7 to calculate the corresponding dynamic AL range according to the Beer-Lambert Law. Fig. 8 shows the AL range of signal transmission at different rates of 20, 50, 80, 100, and 150 Mbit/s compare to the conventional receiver and the receiver with the adaptive control system, respectively. With the increase of transmission rate, the range of transmission distance that the signal can tolerate is gradually reduced, which requires higher stability of optical power. When the transmission rate is 150Mbit/s, the transmission dynamic range is only 1.5AL under the condition without the adaptive control system. After

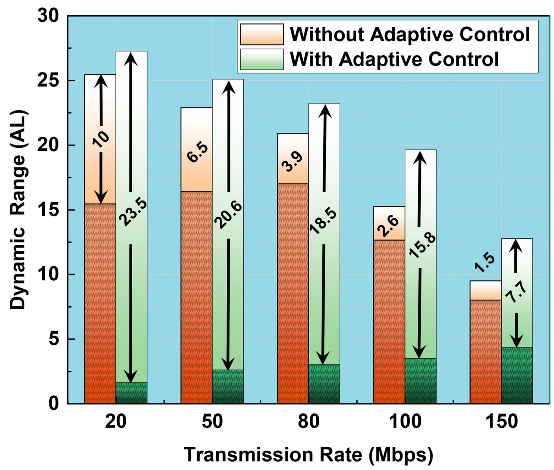

Fig. 8. The attenuation length (AL) dynamic range of signal can be transmitted at different data rates of 20, 50, 80, 100, and 150Mit/s.

using the adaptive control system, the transmission distance had been greatly improved. When the transmission rate is 20, 50, 80, 100, and 150 Mbit/s, the dynamic AL range was 23.5, 20.6, 18.5, 15.8, and 7.7. Compared with the conventional receiving system, the dynamic AL range is expanded by 13.5, 14.1, 14.6, 13.2, and 6.2. Obviously, the adaptive control system for the receiver can effectively improve the transmission dynamic range of the UWOC system, which makes the UWOC system can easily adapt to the complex underwater environment and realize reliable underwater communication.

V. Conclusion

The reliability and stability of UWOC performance under dynamic optical power change of underwater channels has become an important requirement for practical UWOC applications using high-sensitive PMT receivers. In this paper, we analyze and characterize the influence of optical power and the gain of PMT on the UWOC bandwidth through experiments and prove the UWOC performance degradation caused by PMT saturation with excessive received optical power. A low-cost, high-integrated, and small-volume receiver control system and relevant adaptive control strategy are proposed to improve the stability and reliability of the UWOC system by dynamically adjusting the received optical power and PMT gain according to the detected optical signal. The experiment results show that by using the proposed scheme, the dynamic optical power range of the UWOC system can be extended to 68 dB (-63dBm $\sim$ 5dBm) for 100Mbit/s OOK modulation. When the transmission rate is 20, 50, 80, 100, and 150 Mbit/s, the experimental results show the equivalent communication range of UWOC system can be extended by 13.5, 14.1, 17.6, 13.2, and 6.2 attenuation length compared conventional method.

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