Visible diode lasers for high bitrate underwater wireless optical communications

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Abstract: This talk provides an overview of the latest underwater wireless optical communication (UWOC) research from the system to the device level. Besides, studies investigating underwater channel characterization are also described.
OCIS codes: (060.4510) Optical communications; (250.0250) Optoelectronics; (040.5160) Photodetectors.

Numerous human underwater activities, ranging from mineral resource exploiting to marine life discovery and even environment monitoring, creating huge demand of highly reliable, secured and high data rate underwater wireless communication systems, as shown in Fig. 1. Compared with radio-frequency (RF) and acoustic wave underwater communications, underwater wireless optical communications (UWOC) outperform in various aspect, such as unlicensed spectrum, large bandwidth (THz) [1] and low data latency.

Fig. 1. Illustration of underwater human activities [11].

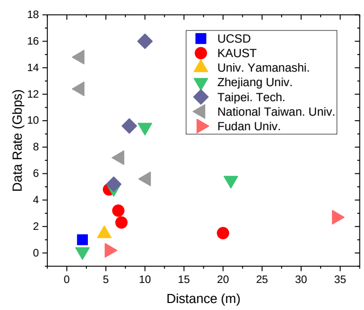

Fig. 2. Advances of recent UWOC.

The first investigation on UWOC was proposed by Karp in 1970's, who characterized channel between underwater and satellite utilizing multiple scattering model [2]. In 1992, using an argon-ion (Ar^+) 514-nm laser, Snow et al. have experimentally demonstrated the first UWOC link with a data rate of 50 Mbps over 5.1 m attenuation length [3]. The first gigabit (1 Gbps) UWOC link was achieved by Hasan et al. in 2008 [4]. In that demonstration, an externally modulated and frequency doubled 532-nm laser was used to send the signal over a 2-m water tank. Recently, high speed, power efficient opto-electronic devices are utilized in realizing even tens of gigabits UWOC links. This includes light emission diodes (LEDs) [5], laser diodes [6], photodetectors (PDs) [7], amplifiers and even integration of these devices [8]. Oubei et al. demonstrated a 2.3-Gbps, 7-m UWOC link with a directly modulated 520-nm laser diode [9]. To achieve higher data rate, some more spectrum efficient modulation technique, such as orthogonal frequency division multiplexing (OFDM) and pulse amplitude modulation (PAM), are adopted in UWOC in the last few years. Kong et al. have experimentally achieved a 9.51-Gbps, 10-m UWOC link by employing 32-quadrature amplitude modulation (QAM) OFDM modulation schemes. Besides, a 450-nm blue GaN laser diode modulated by pre-leveled 16-QAM OFDM was employed, implementing a UWOC link with data rate up to 12.4 Gbps over 1.7 m [1]. Furthermore, Huang et al. have established filtered multicarrier 16-QAM OFDM UWOC link, achieving a data rate of 14.8 Gbps and a transmission distance of 1.7 m [6]. Beside the OFDM, a data rate of 16 Gbps UWOC system over 10 m transmission distance was implemented with the PAM-4 by Liu et al in 2016 [10]. While pursuing high data rate UWOC, by taking advantages of low seawater absorption in visible portion of electromagnetic (EM) waves, these UWOC links are even demonstrated to have transmission distance over tens of meters underwater. Shen et al. achieved the first Gbps UWOC link over 20 m with a directly modulated 450-nm laser diode [11]. Based on this study, a 21-m, 5.5 Gbps UWOC link with OFDM modulation was further demonstrated by Chen et al. in 2017 [12]. The longest distance with a Gbps data rate UWOC system was demonstrated by Liu et al., who used a directly modulated 520-nm laser diode and a transmission distance of 34.5 m was achieved [13]. The recent advances of UWOC based on the visible light were summary in Fig. 2 [4-6, 9-21]. Besides these data transmission underwater, a high quality video streaming was achieved in real ocean water [22].

However, realistic UWOC performance should take into account the various practical scenarios in actual undersea environment, which will alter the light propagation characteristics in water. These factors include microscopic particulates suspended in various ocean waters, turbulence resulted from the change in refractive index introduced either by temperature or by salinity gradient, bubbles, etc. In the presence of microscopic particulates suspension and dissolve organic matters in different ocean waters, absorption and multiple scattering process will cause irreversible loss of optical intensity and severe temporal pulse broadening, respectively [23], and these results will in turn degrade the 3-dB channel bandwidth [24]. While aforementioned works are mainly based on blue-green laser/LED under clear water condition. Nevertheless, the effects of such suspension particulates and dissolved organic matters requires further in-depth study. Xu et al. numerically studied the feasibility of enhancing the channel bandwidth by deploying red laser in a UWOC system mainly due to the smaller scattering effect in the longer-wavelength [25]. Based on this study, Lee et al. experimentally demonstrated the performance enhancement by utilizing a near-infrared (NIR) laser, which shows the overall frequency response of the system gains an increment up to few tens of MHz with increasing particulates' concentration [26]. Besides mitigating the effect of suspension particulates, longer optical wavelengths also show the ability to mitigate the turbulence originated from temperature or salinity gradient. Oubei et al. experimentally measured the scintillation index for the red-green-lasers under turbulence, and red laser experiences much smaller signal fading as compared to the blue-green lasers [27].

On the other side, instead of using longer wavelength (red/NIR) to achieve high communication performance and to circumvent the above-mentioned scattering effect, it is feasible to construct a non-line-of-sight (NLOS) configuration by taking advantage of light scattering. In a NLOS underwater system, the field-of-view (FOV) for both transmitter and receiver are not directed towards each other. Rather, by scattering from the water molecular, suspension particles etc., the transmitter radiation will be redirected multiple times before arriving at the detector. Thus, NLOS communications relax the requirement of positioning, acquisition, and tracking (PAT). Sun et al. reported the first underwater ultraviolet (375-nm) NLOS communication system, and experimentally measured the effect of geometries, water turbidity, and wavelengths based on path loss measurements [28]. They demonstrated that NLOS UWOC link can be significantly enhanced using the ultraviolet (375-nm) laser. It holds promises for circumventing the problems of scintillation, deep-fade, complete signal blockage in LOS UWOC.

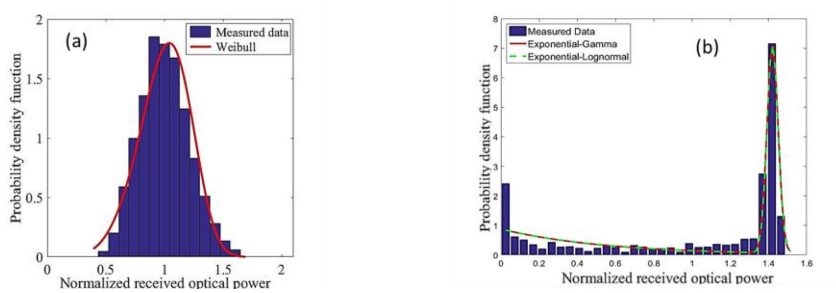

Fig. 3 UWOC turbulence related studies: (a) Weibull fitting distribution and the corresponding measured data histogram for a salinity gradient of $5\times10^{-2}\mathrm{g}\cdot L^{-1}\cdot cm^{-1}$. (b) the histogram of the measured data along with the exponential-Gamma and exponential log-normal model for fresh water for a bubble level equal to 7.1 L/min.

In fact, a channel model is necessary to reflect the realistic performance evaluation of UWOC systems. Factors affecting such UWOC performance can be classified into two categories — inherent optical properties (IOPs) and apparent optical properties (AOPs). IOPs refer to the water medium related properties and do not rely on the light field geometry. The two fundamental IOPs are absorption and volume scattering function (VSF) from which the scattering coefficient can be derived [29]. The behavior of light propagation affected by IOPs can be modelled by radiative transfer equation (RTE) [30]. AOPs, on the other hand, include the properties that depend on both the medium and light field structure such as collimation and diffusion [31]. While the majority of studies for UWOC channel models focus on characterizing the absorption and scattering processes, the model to describing the channel performance in the presence of turbulence introduced by temperature or salinity gradient, should also be emphasized. Yi et al. proposed to use log-normal distribution, which has already been used to represent turbulence-induced signal fading in free-space under weak turbulence, to characterize the weak oceanic turbulence with the probability density function [32]. Two more advanced models called Weibull distribution and Generalized Gamma Distribution (GGD) are found to be more suitable to model the statistical behavior of the measured irradiance for salinity [33] and temperature [34] induced turbulence, respectively. In oceans, bubbles can also affect UWOC performance, and this can be modelled by exponential-Gamma model [35]. Also, Oubei et al. demonstrated the feasibility of turbulence mitigation by adopting beam expansion [35]. Fig. 3(a) illustrates the Weibull fitting distribution and the corresponding measured data for a salinity gradient of $5\times10^{-2}\mathrm{g}\cdot L^{-1}\cdot cm^{-1}$, and Fig. 3(b) shows the histogram of the measured data along with the exponential-Gamma and exponential log-normal model for fresh water for a bubble level equal to $7.1L\cdot\min^{-1}$. We have thus verified the performance of UWOC system in both uniform and turbulent channels. A review of the recent advances in UWOC link were also published in [36].

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