Implementation of Simultaneous Underwater Optical Wireless Communication and Solid-State Lighting

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***Abstract*—We demonstrate the design and implementation of a simultaneous underwater optical wireless communication and solid-state lighting system. It can achieve a data rate of 1.7 Gbps with a color rendering index of 76.3.**

Keywords—Underwater wireless optical communication, Solid-state lighting, Quantum Dots

I. Introduction

The ocean covers over 70 % of the Earth's surface, and ocean exploration is becoming increasingly important globally due to its economic, strategic, and scientific significance [1, 2]. Tremendous research efforts have been put on exploring the ocean with an efficient and reliable underwater illumination and communication system. There are several techniques used for underwater wireless communication, including acoustic communication, radio wave communication, and optical wireless communication (OWC). The acoustic wireless link propagates well in water compared to radio waves and visible wireless links, but it cannot support high-speed communication due to limited bandwidth. Radio waves can also be utilized for underwater wireless communication. However, the conductive nature of seawater acts as a natural barrier to radio waves, making underwater communication quite challenging and limiting the communication distance to a very short range [3].

On the other hand, the attenuation of optical signals in the blue-green spectrum region is relatively low in seawater. Therefore, underwater optical wireless communication (UOWC) has gained increasing research interest in recent years as a promising technology for high-speed and long-distance communications in aquatic media [4-6]. UOWC offers several advantages over existing wireless communication systems, including high energy efficiency, high data rate, network security, and low operation and installation cost.

In addition, UOWC can be combined with underwater solid-state lighting (SSL) to realize the underwater potential for applications requiring high illumination. Developing a comprehensive understanding of underwater lighting and how lighting parameters change underwater is critical for system design. Light parameters can also play a major role in some processes depending on the operating environment. Different underwater operations need different illumination characteristics; some activities need high-quality illuminations, images, and videos, such as seafloor monitoring, biological observation, subsea photography, and oceanographic study [7, 8]. Therefore, high-efficiency and high-quality SSL are crucial for deep-sea exploration and undersea human activities. In an underwater environment, using polychromatic light for high illumination and communication is challenging due to water absorption and scattering, which limit illumination and transmission distances. There are limited studies that investigate underwater illumination and communication simultaneously. However, some researchers have proposed RGB LDs/LEDs for high-data UOWC and high-quality underwater SSL. In 2021, Xu et al. demonstrated a bidirectional white light VLC and UOWC convergent system based on RGB laser diodes [9]. Liu et al. experimentally demonstrated underwater OWC and SSL with a CRI of 69 and an aggregate data rate of 9.7 Gbps using RGB LDs [10]. The results demonstrate excellent performance that can be achieved with high data rates. However, the proposed systems require complex and costly infrastructure. The deployment and maintenance of such a system is a time-consuming and labor-intensive task in an underwater environment. Therefore, there is a need for a simple and cost-efficient alternative to implement underwater high-speed OWC and high-quality SSL.

In recent years, semiconductor quantum dots (QDs) have emerged as a promising candidate for next-generation OWC and SSL devices due to their exceptional optical properties.

Various color converter quantum dots are dispersed in silicone resin to form films with a high color rendering index (CRI > 90) [11-13]. However, organic resins in these films are susceptible to heat and water, reducing their lifespan and making them unsuitable for underwater applications. To overcome these limitations, a combination of blue LD and color conversion materials (CCMs) in a glass cavity could be used for underwater OWC and SSL.

In this study, we proposed and experimentally demonstrated a novel underwater OWC and SSL using a glass cavity filled with cesium lead bromide ($CsPbBr_3$) and cadmium selenide/zinc sulfide (CdSe/ZnS) as a CCMs, which was excited by blue LD. The fabrication process of glass cavity filled with CCMs is shown in Fig. 1, and more details on the properties of CCMs can be found in [14]. Our facile approach of adopting CCMs in a glass cavity ensures environmental and thermal stability, making it highly promising for underwater OWC and SSL due to its excellent optical properties and stability. The fabricated glass cavity filled with CCMs can be completely submerged in a water bath without any structural or material degradation. Notably, our proposed system sheds light and paves the way toward CCMs-based underwater OWC and SSL simultaneously.

The rest of this paper is organized as follows: The experimental setup of the proposed system is described section II. Section III presents experimental results and discussion. Finally, we conclude the paper in section IV.

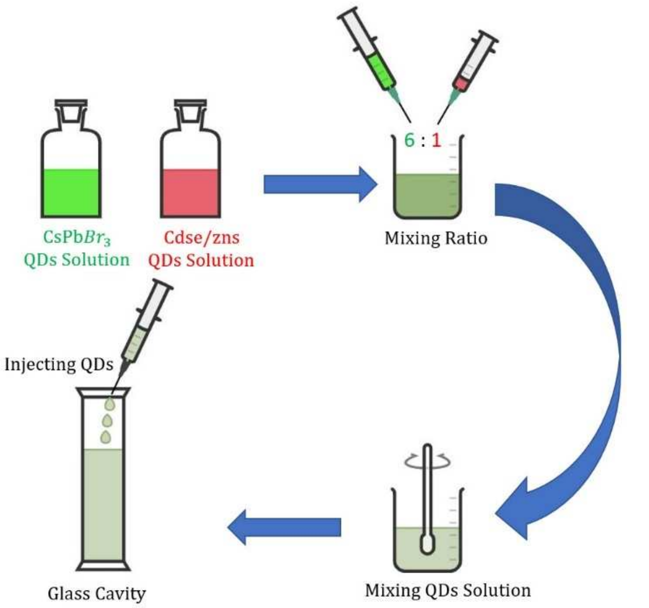

Fig. 1. Fabrication process of CCMs in glass cavity.

II. Experimental Setup

The schematic diagram of proposed experimental setup for underwater OWC and SSL is illustrated in Fig. 2, with an inset showing a photograph of the setup. The frequency response of the system was measured using a network analyzer, while the transmission performance was measured using a bit error rate tester (BERT). Non-return-to-zero on-off keying (NRZ-OOK) signals from the BERT and direct current were combined to modulate the blue LD. The optical signal emitted by the LD stimulated the CCMs to generate luminescent white light, which was collimated into a photodetector after transmitting through a 2 m water tank. The BERT captured the generated electrical signal. The electroluminescence (EL) spectra of the white light were measured using an Ocean Optics HR4000 spectrometer, while the characteristics of the generated white light, such as correlated color temperature (CCT), color rendering index (CRI), and Commission Internationale de L'Eclairage CIE, were measured using an OHSP spectral and illuminance analyzer.

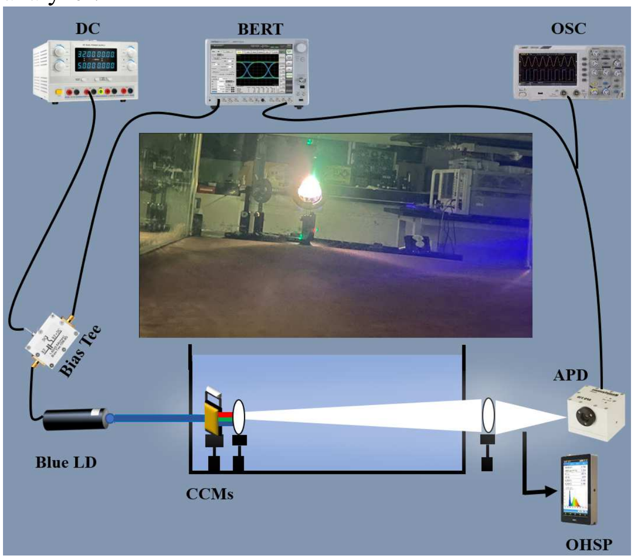

Fig. 2: Schematic diagram of the experiment setup. Inset: photography of the experimental setup.

III. Results and Discussion

The relationship between light output power, current, and voltage (P−I−V) of the blue LD is shown in Fig. 3. The received optical power of down-converted red and green lights versus the driving currents is shown in the inset of Fig. 3. Green and red pass filters were used to measure the optical power of green and red light, respectively. After adhering the CCMs, the slope of power to current decreases due to stock shift, scattering, reflection, relevant absorption, and beam divergence.

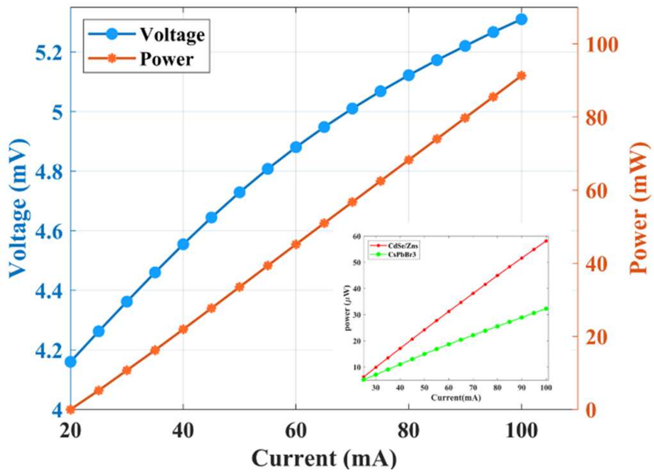

Fig. 3: P−I−V characteristic of the blue laser diode. Inset: received optical power of down-converted red and green lights versus the driving currents.

We evaluated the stability of a glass cavity filled with CCMs in water by directly submerging the cavity in water for 20 minutes. The electroluminescence spectra of down-converted lights are shown in Fig. 4. The inset shows a glass cavity filled with CCMs in a water bath under blue LD light illumination. The intensity decay of down-converted light under various operation times extracted from Fig. 4 is shown in Fig. 5. The results indicate that after 20 minutes of testing in water, the efficiency of down-converted green and red light showed a reduction of 11% and 8%, respectively.

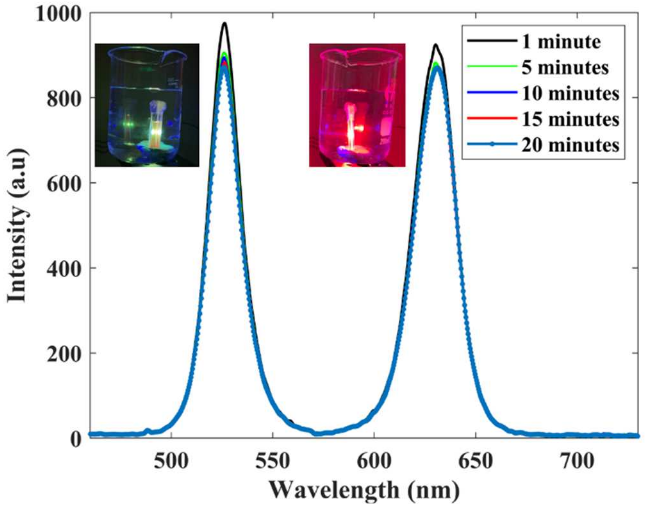

Fig. 4: EL spectra of down-converted lights under various operation times. Inset: glass cavity filled with CCMs in a water bath under blue LD light illumination.

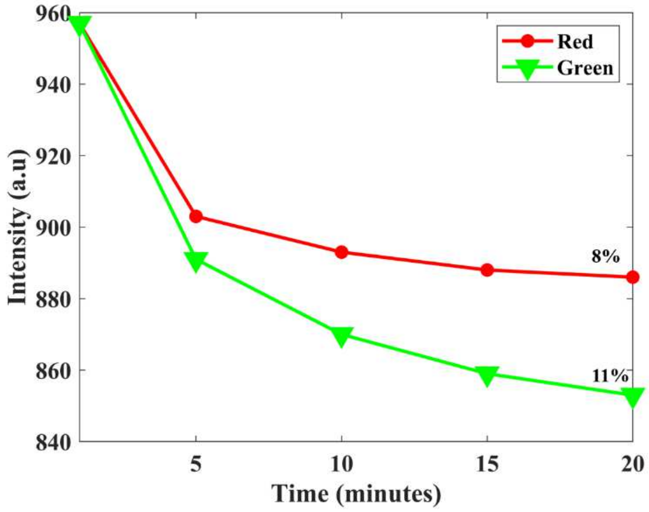

Fig. 5: Intensity decay of down-converted lights under various operation times.

To evaluate the illumination performance of the generated white light in an underwater environment, we examined the EL spectra, CCT, CRI, and CIE chromaticity coordinates. Fig. 6 displays the EL spectra of the white light under bias currents ranging from 30 mA to 70 mA. We considered 42 mA bias current as the optimal current for underwater OWC and SSL. The spectrum features blue, green, and red-light emissions from the blue LD, $CsPbBr_3$, and CdSe/ZnS, respectively, with peak wavelengths of 450, 526, and 630 nm. The generated white-light source has a high CRI of 76.3 and a CCT of 4909 K. Typically, a CRI of 70 or higher is recommended for indoor and underwater lighting applications. However, the specific CRI requirements may vary depending on the intended use of the lighting. The bias current and CCMs concentration ratio can further alter the CRI of the light source. Fig. 7 displays the CIE 1931 chromaticity coordinates of the generated white light source, which are (0.3461, 0.3377), close to the ideal CIE white light value (0.3333, 0.3333) in the color space.

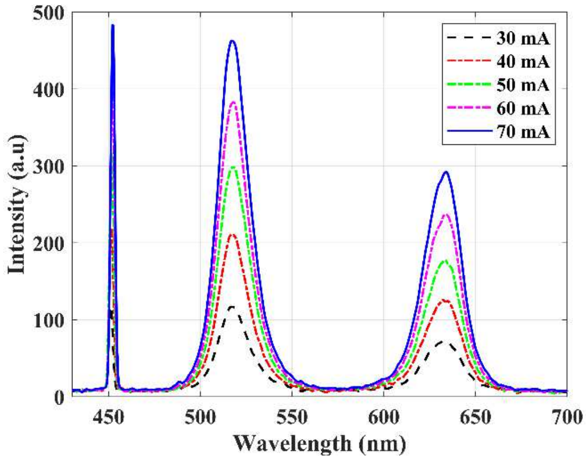

Fig. 6: EL spectra at different bias current.

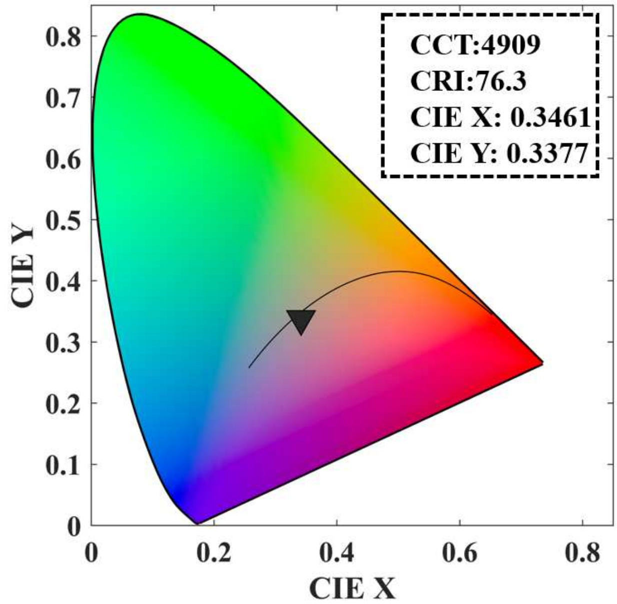

Fig. 7: CIE chromaticity of white light.

The small-signal frequency response and bit error rate (BER) were measured to investigate the modulation bandwidth and underwater wireless communication performance. At an optimized current, the system frequency response is shown in Fig. 8. The maximum 3 dB bandwidth achieved was 820 MHz, making it a promising application for high speed underwater OWC. The NRZ-OOK modulation scheme was applied to the proposed system to investigate its transmission capacity. The BER performance under various data rates is shown in Fig. 9, where the maximum data rate is 1.7 Gbps with a BER of $2.0 * 10^{-3}$ over a transmission distance of 2 m underwater tank, adheres to the standard threshold of forward error correction (FEC) is achieved. Additionally, we can estimate the transmission performance of the systems using the eye diagram. Open eye diagrams were observed at 1.0 and 1.7 Gbps, as shown in the inset of Fig.9, indicating that the proposed system is capable of a high data rate up to 1.7 Gbps. These results provide an innovative approach to the simultaneous implementation of underwater OWC and SSL significantly.

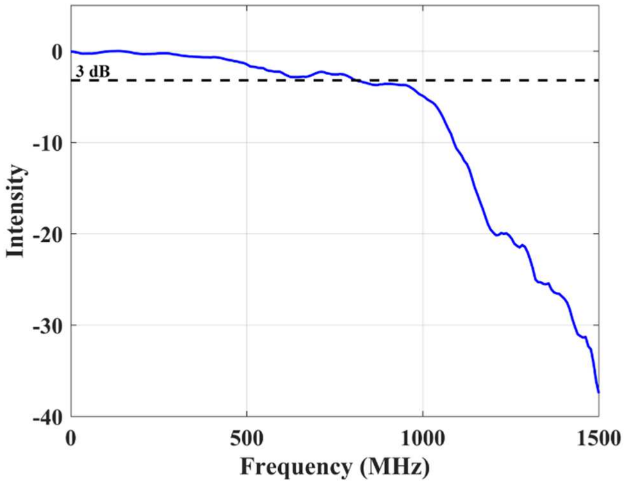

Fig. 8: Frequency response of system

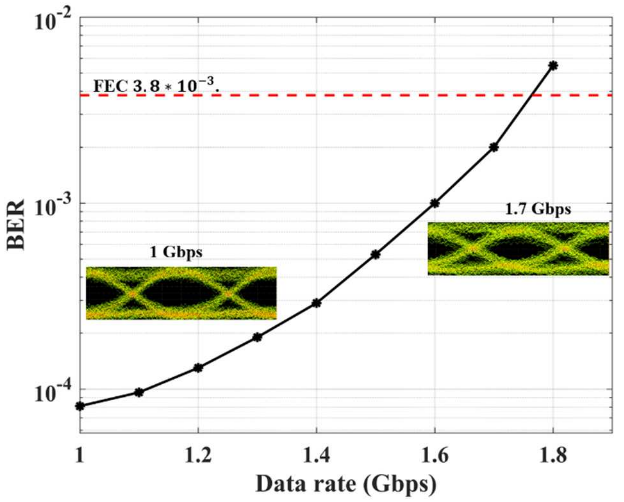

Fig. 9: Measured bit-error rates at different data rates. Inset Eye diagram at 1 Gbps and 1.7 Gbps.

IV. Conclusion

The proposed system, as demonstrated, has significant potential for various underwater applications, including environmental monitoring, biological observation, and subsea photography. The system achieves a data rate of 1.7 Gbps using a non-return-to-zero on-off keying modulation, and the generated white-light source has high color rendering index of 76.3, a correlated color temperature of 4909 K, and CIE coordinates of (0.3461, 0.3377). Overall, our findings provide valuable insights into the simultaneous implementation of underwater optical wireless communication and solid-state lighting, and may aid researchers in further developing this technology for practical applications.

V. ACKNOWLEDGMENT

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