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Design and Evaluation of Optical Wireless Communication Systems for Underwater IoT Applications

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***Abstract*— This paper investigated the deployment of Optical Wireless Internet of Things (OWIoT) systems within underwater environments, addressing the significant challenges faced by RF communication, including signal attenuation and interference. The advantages of optical wireless communication, such as higher bandwidth and enhanced security, were highlighted as particularly suitable for aquatic conditions. Through simulations conducted using Ansys Zemax software, LEDs operating at a 625 nm wavelength were identified as optimal, demonstrating a potential frequency bandwidth of 10.52 MHz at a bias current of 150 mA. This configuration was found to optimize signal integrity and extend communication range underwater. Subsequent experimental validation confirmed the simulated performance, with consistent data transmission over a 1000 mm underwater path and minimal signal degradation being achieved. The integration of simulation insights with empirical evidence was shown to solidify the foundation for advancing OWIoT technologies, offering a robust solution for underwater data communication and marking a significant advancement in overcoming the barriers of underwater IoT deployments.**

***Keywords*— Optical Wireless Underwater, Wireless IoT Applications, LED Optical Transmission, styling, LED Transmission**

I. Introduction

In contemporary times, wireless Internet of Things (IoT) technology facilitates wireless communication among devices to gather data [1], conduct analysis, and enable automation processes. This technology employs various connectivity protocols [2], including Wi-Fi, Bluetooth, and cellular networks to forge robust communication infrastructures. Equipped with sensors [3], IoT devices are capable of acquiring data, which is then processed locally through edge computing. Furthermore, these devices exploit sophisticated data analytics and machine learning methodologies to extract meaningful insights. Among the primary concerns in the deployment of IoT systems are ensuring robust security, achieving scalability, maintaining interoperability, and optimizing energy efficiency.

Building on the foundation laid by wireless IoT technologies, Radio Frequency (RF) communication emerges as the predominant method for information exchange within this realm [4]. This communication modality facilitates data transmission over considerable distances, utilizing air as the propagation medium. The selection of an appropriate technology for a given application is governed by multiple factors, including the required bandwidth for data transfer and the distances over which the data must travel. To cater to the diverse requirements of IoT deployments, an array of wireless communication technologies, from Wi-Fi and Bluetooth to Zigbee and cellular networks, is employed. These technologies are adept at addressing the demands of data transmission distances, speed, power consumption, and deployment costs. Each technology brings distinct

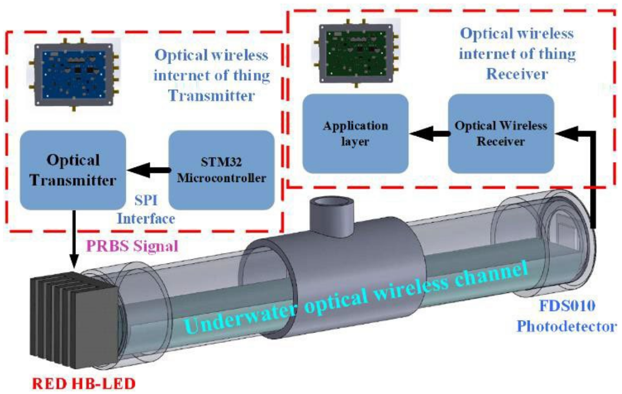

Fig. 1 A diagram of an underwater OWIoT.

advantages, tailored to meet the specific needs of various IoT applications and adapt to differing environmental conditions.

Building on the exploration of wireless communication technologies within the IoT domain [5-8], certain Wireless IoT technologies have been recognized for their remarkable ability to transport data across extensive distances. Notably, technologies such as Long Range (LoRa), Narrowband IoT (NB-IoT), and Sigfox stand out for their capacity to facilitate data transmission well beyond the 10 km mark. The research highlighted by [9] delves into the application of LoRa technology for this purpose, with a particular emphasis on Multi-hopping Data Transmission Techniques. Such methodologies enable the conveyance of data over distances surpassing 10 km, thereby illustrating the formidable potential of LoRa technology in extending the reach of IoT connectivity across vast expanses.

The application of Wireless IoT in underwater environments introduces challenges that markedly contrast with terrestrial conditions [10]. These include pronounced signal attenuation, heightened noise levels, limited bandwidth, and challenging environmental factors [11]. To navigate these hurdles and enable effective IoT applications beneath the water's surface [12], the adoption of innovative communication protocols and advanced hardware solutions becomes imperative. Specifically, the utilization of RF for underwater communication encounters substantial difficulties, such as increased signal attenuation, diminished penetration, substantial absorption, and notable interference, all of which contribute to a degradation of signal quality. These issues collectively curtail communication range and complicate system architecture, diminishing RF technologies' suitability for underwater use. In this context, alternative communication modalities, including acoustic and optical technologies, emerge as more viable options for maintaining high-quality communication in subaquatic settings.

Optical communication offers a wide range of benefits for underwater applications, including high bandwidth, low attenuation, little interference, directionality, better security, and immunity to electromagnetic interference. However, due to its distinctive properties, it is the ideal option for dependable and secure data transfer in aquatic settings.

In this paper, the implementation of optical wireless communication within underwater settings for IoT applications is thoroughly investigated. The focus centers on the development of Optical Wireless Internet of Things (OWIoT) circuits, utilizing LEDs operating at a wavelength of 625nm. This investigation leverages the Ansys Zemax software to simulate optical communication scenarios in underwater environments. Furthermore, a series of measurement tests are conducted to assess data transmission underwater using a specifically designed experimental setup. This research explores the feasibility and efficiency of optical wireless communication technologies in facilitating IoT functionalities in submerged environments. To illustrate the conceptual framework and operational blueprint of the OWIoT system under investigation, a comprehensive schematic is illustrated in Fig. 1.

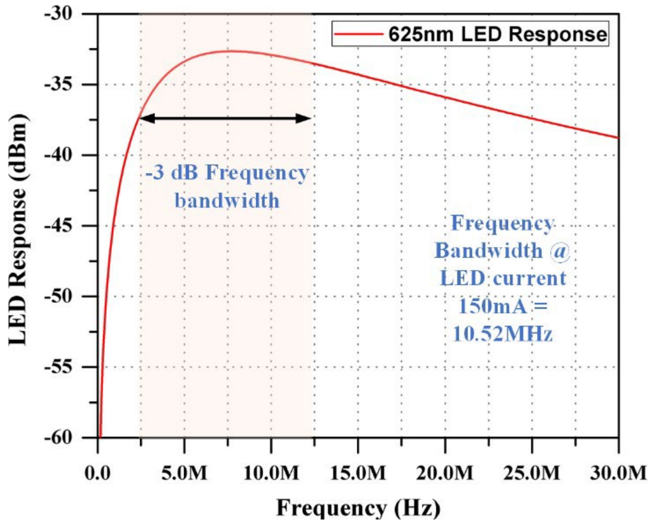

Fig. 3 The simulation results of the frequency response of the LED.

II. Simulation of Optical Underwater Communication

This section meticulously outlines the methodology employed for conducting underwater optical analysis using Ansys Zemax software. The simulation setup incorporates an LED light source, specifically selected for its operation at a 625 nm wavelength, to emulate underwater optical conditions closely. Combinations of optical lenses are integrated into the setup to refine the analytical process further. Additionally, the

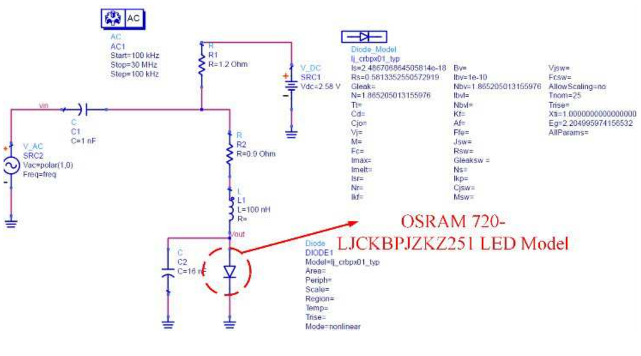

Fig. 2 The equivalent circuit of a 625nm LED with the Keysight ADS program.

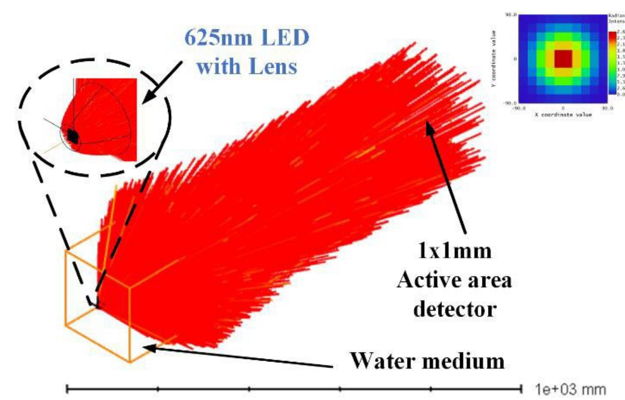

Fig. 4 The simulation results of the frequency response of the LED.

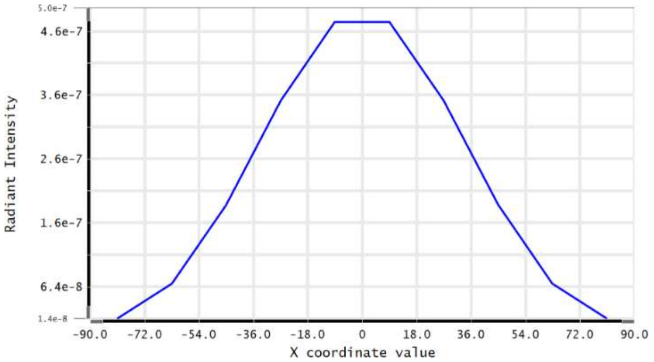

Fig. 5 The simulation results of the frequency response of the LED.

LED's characteristics are rigorously modeled within the Keysight ADS program [13], significantly enhancing the accuracy of the simulations. This comprehensive approach facilitates a detailed examination of optical efficiency in submerged environments, thereby advancing optical wireless communication systems tailored for such unique settings.

A. LED Characteristics Simulation

In this paper, an LED (OSRAM: 720-LJCKBPJZKZ251) emitting at a wavelength of 625 nm and outputting 1 W of red light is selected for analysis. This choice is informed by existing literature [14], which indicates that longer wavelengths experience less signal attenuation in underwater scenarios. Leveraging this knowledge, the goal is to minimize signal degradation and bolster the reliability of optical communication in submerged contexts. The LED's characteristics are simulated using Keysight ADS, where the model parameters series resistance (R2) at 0.9 Ω, inductance (L1) at 100 nH, and diode capacitance (C1) at 16 nF are meticulously defined. These parameters are seamlessly integrated into the LED model, incorporating diode characteristics from the SPICE model provided by OSRAM. The construction of this LED model adheres to methodologies previously delineated by [15], offering a robust framework for the simulations. The setup for these simulations is depicted in Fig. 2.

In applications involving LEDs within the OWIoT system, the bias current is carefully selected at 150 mA to optimize power efficiency. It is imperative to acknowledge the significant influence of bias current on the LED's bandwidth, which, in turn, dictates the data transmission rate. Elevating the bias current enhances the LED's bandwidth, facilitating quicker data transmission at the expense of increased power consumption. Consequently, selecting an optimal bandwidth is paramount to balancing energy efficiency within the system. It is essential for managing energy consumption in the system.

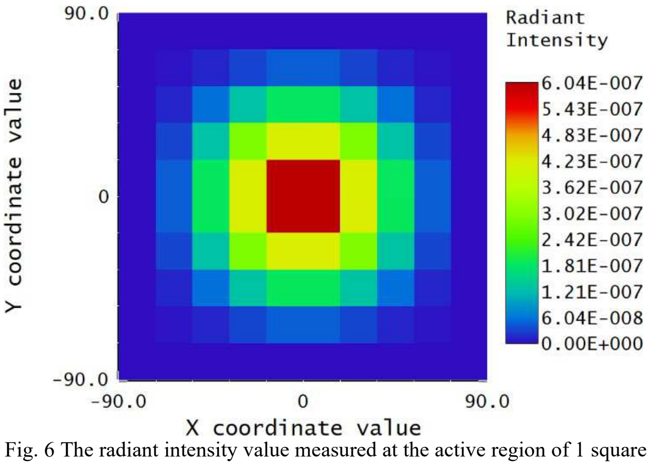

Fig. 6 The radiant intensity value measured at the active region of 1 square millimeter.

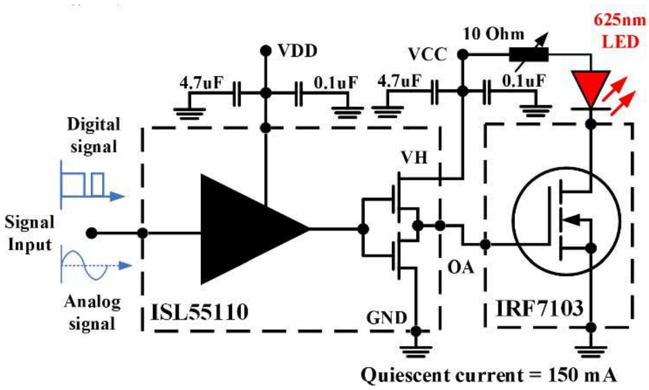

Fig. 7 Schematic diagram of the OWIoT transmitter.

This paper emphasizes achieving low-speed data transmission rates, specifically capped at 100 kbps, to align with the prevalent requirements of IoT systems. Such systems customarily demand the transmission of relatively small data volumes over channels characterized by constrained bandwidth. As shown in Fig. 3, simulation results reveal that modulation using an analog signal in the form of a sine wave waveform at a bias current of 150 mA results in a frequency bandwidth of 10.52 MHz. This finding underscores the research's alignment with the energy efficiency and bandwidth optimization goals for IoT applications. Furthermore, the design approach adopted here thoughtfully includes flexibility for bandwidth expansion, ensuring the system's readiness to adapt to future needs for higher-speed data transmission, thereby offering a robust framework for the advancement of optical wireless communication in IoT contexts.

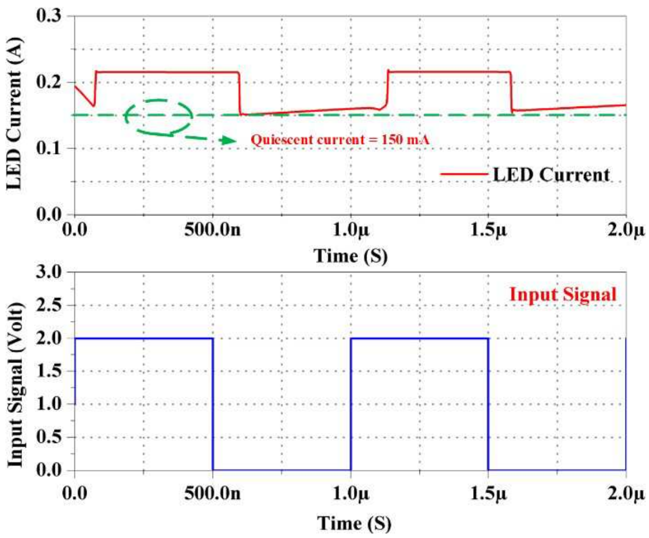

Fig. 8 The simulation results of the OWIoT transmitter using the TINA software.

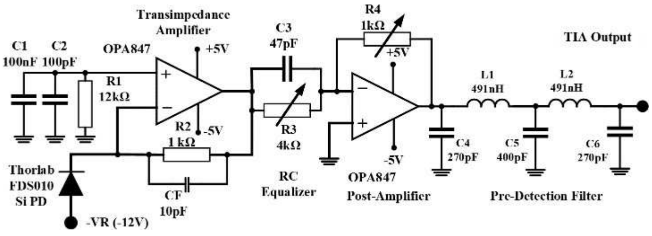

Fig. 9 The schematic diagram of OWIoT receiver circuits.

B. A Simulation of Optical Underwater Conditions

Ray tracing principles [16] are utilized through the Ansys Zemax program to simulate the optical underwater communication channel. Inputs for the simulation incorporate the LED characteristics delineated from preceding simulation outcomes alongside the ray file model provided by the OSRAM manufacturer to ensure precision in simulation. Water is selected as the medium for this simulation. To augment the accuracy of the simulation, an optical lens model, boasting a viewing angle of 25 degrees, is crafted within the Zemax program. Fig. 4 illustrates the Ansys Zemax simulation.

Fig. 5 shows the radiant intensity through a cross-sectional view, where a peak intensity of approximately 60 μW is observed over an active area of 1 square millimeter, aligning with the dimensions of the photodiode's active area. A further illustration is provided in Fig. 6, which utilizes a color scale to present the radiant intensity in the underwater experiment, measured at a distance of 1,000 mm.

C. OWIoT Transmitter Simulation

This section investigates the intricate design of the OWIoT system's end-to-end circuitry, encompassing both transmitter and receiver components. Utilization of the TINA-TI Simulation program [17] is crucial in conducting these simulation tasks efficiently.

Illustrated in Fig. 7 is the operational layout of the OWIoT transmitter circuit. This configuration incorporates high- speed MOSFET drivers, specifically the ISL55110, tasked with driving the input signal for amplification through the IRF7103.

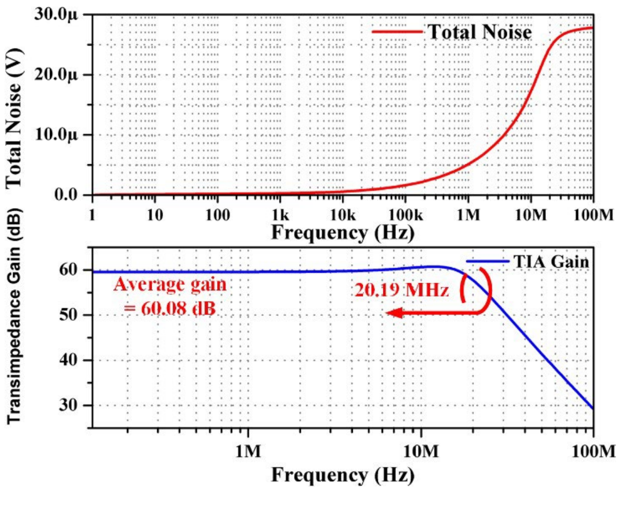

Fig. 10 The Simulation results for the gain and total noise of the Transimpedance amplifier (TIA).

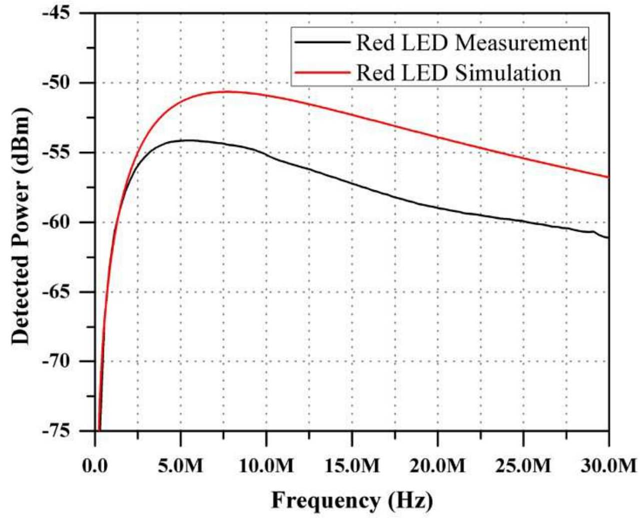

Fig. 11 The experimental results of frequency response under underwater conditions at a distance of 1,000 mm.

Following amplification, the signal is directed into a 1W LED, emitting light at a wavelength of 625 nm. The modulation process of the input signal utilizes the carrier signal of the LED, maintaining a steady current of 150 mA to ensure the LED's optimal performance.

Fig. 8 presents the simulation results achieved with the TINA program, applying a pulse input signal with an amplitude of 2 V to the circuit. Examination of the LED's output current signal unveils fluctuations that mirror the input signal, oscillating between 60 mA and the LED's stable current of 150 mA. A detailed analysis of the variance between the input signal and the LED current highlights a signal delay estimated at approximately 75 ns. This delay is attributed to the switching response time of the electrical components involved.

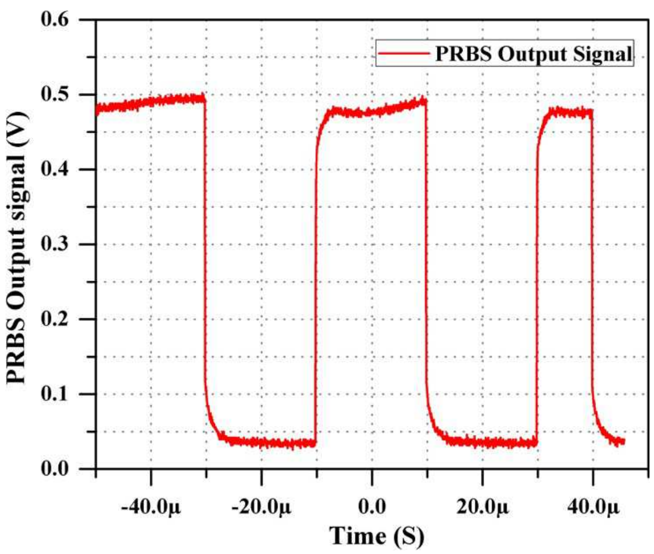

Fig. 12 The experimental results of frequency response under underwater conditions at a distance of 1,000 mm.

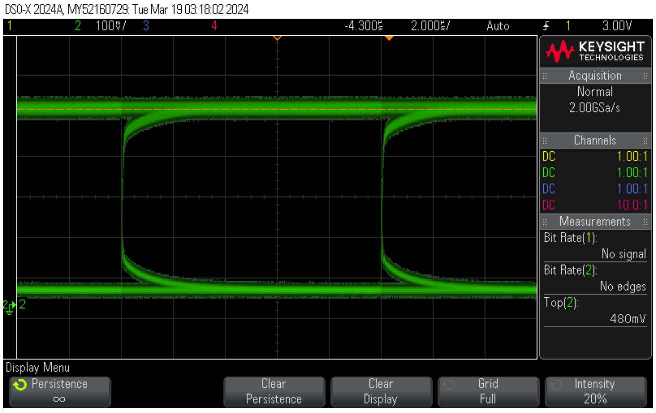

Fig. 13 The experimental results of frequency response under underwater conditions at a distance of 1,000 mm.

D. *OWIoT Receiver Simulation*

Fig. 9 illustrates a detailed schematic view of the OWIoT receiver circuit, comprising four analog sub-circuits: the trans-impedance amplifier, equalizer, post-amplifier, and pre-detection filter, integrated sequentially. The operational framework of this circuit involves two power supply rails, designated as +12 V and -12 V. The latter is utilized to apply a reverse bias (VR) on the photodiode (PD), whereas the former powers a linear regulator that, in turn, generates the necessary +5 V and -5 V for operational amplifier functions. As shown in Fig. 10(a), the simulation results for the trans-impedance amplifier present the noise level measurements, indicating a noise level of 24.07 µV at a frequency of 20 MHz. Additionally, Fig. 10(b) presents an average gain of 60.08 dB within the operational bandwidth, reaching a maximum frequency of 20.19 MHz.

These simulations affirm the OWIoT system's proficiency in data transmission, achieving a bandwidth of 10.52 MHz. Despite a minor delay of approximately 75 ns, the LED efficiently modulates in accordance with the input signals. The trans-impedance amplifier, with its average gain of 60.08 dB and maintained noise levels at 24.07 µV, plays a pivotal role in ensuring the integrity of the transmitted signal. Collectively, these findings underscore the system's capability for reliable data transfer, laying the groundwork for subsequent enhancements in the OWIoT system's performance.

III. Measurement Results

This section investigates the experimental outcomes, particularly focusing on analog transmission frequency response characteristics in aquatic environments. The examination encompasses the system's ability to manage a spectrum of frequencies under analog signal conditions. Subsequently, the investigation extends to the analysis of results derived from employing digital modulation techniques. This phase involves evaluating the achievable data transmission rates within an underwater setting and determining the bandwidth allocated for digital modulation applications.

A. *Analog Modulation Scheme Measurement*

Fig. 11 presents the frequency response of analog signal transmission at an underwater distance of 1,000 mm. Normalization of these experimental results reveals that an increase in the LED's bias current leads to an expansion of the frequency bandwidth, specifically the 3 dB bandwidth. The findings indicate that the maximum frequency bandwidth achieved, as shown in Fig. 11, reaches 10.52 MHz when the LED operates at a bias current of 150 mA.

Furthermore, Fig. 11 elucidates the comparison between the frequency responses obtained from simulations and those measured experimentally under underwater conditions. Notably, a slight discrepancy is observed in the peak signal levels, with the simulation displaying -50.65 dBm against the experimental value of -54.14 dBm. Despite this variance, the frequency bandwidth remains consistent, underpinning the inference that the stability of the frequency bandwidth is predominantly influenced by the LED's bias setting rather than by external environmental factors.

B. *Digital Modulation Scheme Measurement*

The implementation of the digital modulation scheme incorporates a pseudorandom binary sequence (PRBS) as the input signal deliberately limited to a maximum data rate of 100 kbps. This specification is deliberately chosen to reflect the design ethos of the underwater OWIoT, where the emphasis is placed on low-speed data transmission for enhanced energy efficiency.

Fig. 12 illustrates the experimental data capturing the OWIoT receiver's output signal, characterized by a PRBS signal with an approximate intensity of 0.5 V. The signal waveform analysis indicates a high level of quality, suggesting an exceedingly low rate of errors during data transmission. Fig. 13 illustrates the outcomes of employing the digital modulation technique through an eye diagram. This form of representation yields critical insights into the signal's quality, offering a means to assess potential interference or distortion within the communication channel.

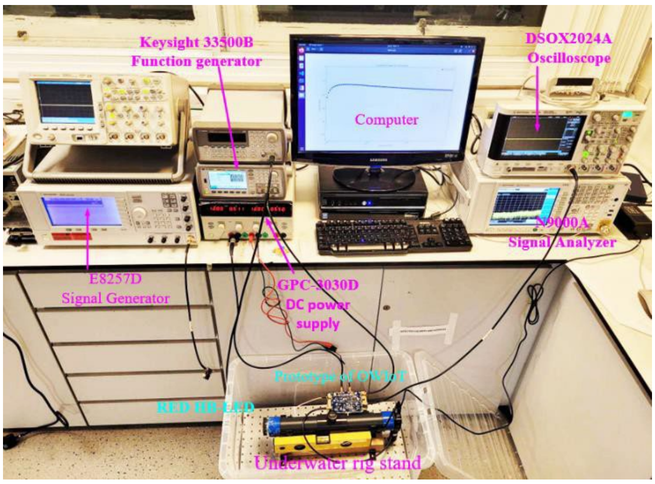

Fig. 14 The test stand and standard measurement instruments used in the investigation.

In underwater optical wireless communication, an increase in the LED's bias current is noted to broaden the frequency bandwidth, achieving a peak of 10.52 MHz at a bias current of 150 mA. Although minor discrepancies in signal level are observed between the simulated and actual measurements, the frequency bandwidth exhibits remarkable stability, predominantly influenced by the LED bias setting. The utilization of a PRBS signal, capped at a 100 kbps data rate, is strategically aligned with the system's design to prioritize low-speed transmissions. The evaluation of the OWIoT receiver's output underscores the PRBS signal's high quality, with negligible error rates. An eye diagram analysis further corroborates the signal's integrity and minimal distortion, underlining the system's effectiveness in digital modulation under aquatic conditions.

IV. CONCLUSION

The paper presents the viability and efficacy of deploying OWIoT systems in underwater environments, addressing the substantial challenges of traditional RF communication methods. Using Ansys Zemax software for simulation and rigorous empirical testing, the research validates LEDs with a 625 nm wavelength as optimal for such applications, achieving a potential frequency bandwidth of 10.52 MHz at a bias current of 150 mA. These findings highlight the system's capability to optimize signal integrity, extend communication range underwater, and confirm the simulated performance with consistent data transmission and minimal signal degradation over a considerable distance. This investigation contributes significantly to the advancement of OWIoT technologies, laying a foundational framework for future research and development efforts to enhance underwater communication solutions for IoT applications. The successful integration of simulation insights with empirical evidence offers a promising pathway for overcoming the complexities of underwater IoT deployments, thus opening new avenues for exploration and innovation in optical wireless communication.

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