Experimental Study on the Effect of Water Salinity in the Underwater Optical Wireless Communication (UOWC) Channel

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***Abstract*—The Industrial Revolution 4.0 era has triggered the interest towards Underwater Optical Wireless Communication (UOWC) as enabling technology for underwater applications. However, UOWC is affected by issues in the underwater optical channel, such as absorption, scattering, and turbulence. Previous studies primarily focused on absorption and scattering, with the impact of underwater optical turbulence often being overlooked. This turbulence can cause significant signal intensity fluctuations at the receiver, leading to poor UOWC system performance. Recent research tends to oversimplify turbulence by assuming it remains constant even though factors like water temperature and salinity affect turbulence variation. Therefore, this study aims to explore how salinity affects UOWC through practical experiments. The experimental set-up is developed consisting of a transmitter, receiver, and a glass chamber to emulate the water channel. The green and blue light sources are used to generate optical signal propagation in saline water channel. The interaction between the selected light with the saline water is analyzed by varying the level of salt concentration. Prior to that, the geometrical loss for Light-Emitting Diode (LED) and laser light sources is determined. Then, the attenuation constant, c is estimated and finally the comparison between the calculated and measured power is made. The analysis reveals that the received light intensity decreases. The estimated c increases as the salt concentration in the water increases indicating the performance of UOWC is declining as the salinity of the water increases. This finding provides insight for designing optimal underwater communication devices and consequently maximizing the UOWC channel capability.**

***Keywords*—Underwater Wireless Optical Communication (UOWC), salinity, laser diodes, Light-Emitting Diode (LED), attenuation**

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I. Introduction

In this Industrial Revolution 4.0 era, the interest towards Underwater Wireless Communication (UWC) as an enabling technology for underwater applications is rapidly increasing. This surge in interest is driven by the recognition that UWC plays a pivotal role in advancing various critical sectors, including marine research, offshore energy production, environmental monitoring, and underwater robotics [1]. In short, UWC refers to data transmission in unguided water environment through wireless carriers namely acoustic waves, Radio Frequency (RF) waves and optical waves. Table I compares the differences between these three carriers.

TABLE I. Comparison between Three Carriers

Types of Carriers	Distance	Frequency	Latency	Data Rate
RF	< 10 m	30–300 Hz	Moderate	Mbps
Optical	< 100m	10^{12}–10^{15} Hz	Low	Gbps
Acoustic	< 20km	10–15 kHz	High	Kbps

On the contrary, acoustic waves are the prevailing choice, as indicated in Table I, primarily because they can reach distances of up to 20 kilometers. Nevertheless, they come with inherent limitations, notably their constrained data rates, which typically support only several hundred kilohertz. This limited bandwidth is inadequate for efficient video transmission. Additionally, acoustic carriers experience significant propagation delays due to the relatively slow speed of sound, and they are susceptible to multipath propagation caused by reflections from the sea floor and refraction due to variations in sound speed [2]. On the other hand, the propagation of Radio Frequency (RF) waves in water is restricted by signal attenuation

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resulting from the elevated electrical conductivity of water at high frequency.

Compared to acoustic and RF carriers, optical waves provide significantly greater transmission bandwidth, enabling data rates of up to 1 Gbps over distances spanning several tens of meters while maintaining low power and mass requirements. Therefore, Underwater Optical Wireless Communication (UOWC) has been identified as a promising technology for Underwater Wireless Communication (UWC) [3]. However, transmitting optical beams underwater presents a formidable challenge due to the dynamic and intricate nature of the UOWC channel. Underwater optical signal propagation contends with three primary factors that degrade its performance: absorption, scattering, and turbulence-induced fading. UOWC grapples with significant obstacles due to the fundamental properties of visible light when it traverses underwater domains. These obstacles include unavoidable photon interactions with water molecules and other particulate substances. Additionally, optical turbulence emerges from the unpredictable fluctuations in the refractive index caused by changes in water temperature, waterflow, and salinity [4].

While many studies on Underwater Optical Wireless Communication (UOWC) have effectively characterized absorption and scattering phenomena, optical turbulence has often been overlooked. Considering that turbulence may be triggered by water salinity, leading to substantial fluctuations in receiver signal strength, this paper examines the impact of salinity on the performance of light wave propagation in UOWC. A basic model of UOWC system has been developed to carry out a series of experiments. This paper has estimated attenuation constants, *c*, based on the obtained experimental results and validated the negative effect of water salinity towards *c*.

The remaining of this paper is organized as follows: Section II presents the recent works and theories related to this work, Section III describes the methodology, Section IV discusses the obtained results and Section V concludes the work.

II. Literature Review

A. Related Works

The propagation of optical beam underwater is very challenging as the UOWC channel is very dynamic and complex requires thorough understanding of the complex physio-chemical underwater environment. Therefore, numerous recent studies have investigated the details of UOWC, exploring new techniques and methods to improve their performance and reach. This section focuses on the review of the characterization of UOWC channel since it is the first essential key step for efficient, reliable, and robust UWOC system design. Table II comprehensively reviews and summarizes recent works on UOWC system.

TABLE II. SUMMARY OF THE RECENT WORKS ON UOWC SYSTEM

z	Author (Year)	Method	Focus of Study
1.	Afifah *et al.* [4]	Experiment	Temperature and turbulence impact on saline water
2.	Kraemer *et al.* [5]	Simulation	Turbidity effects due to absorption and scattering.
3.	Enghiyad and Sabbagh [6]	Simulation	Combined effects of absorption, scattering and turbulence on channel impulse response
4.	Kumar *et al.* [7]	Experiment	Analysis on the effect of salinity
5.	Kumar *et al.* [8]	Experiment and simulation	Effects of system parameters on transmission depth
6.	Elamassie, and Uysal [9]	Analytical	Model the vertical underwater link as a cascaded fading channel with different values of salinity and temperature form non-mixing layers.
7.	Ijeh *et al.* [10]	Analytical	Analysis of a vertical link subject to oceanic turbulence and pointing errors and selection of link parameters to optimize link performance
9.	Mahmoud *et al.* [11]	Simulation	Dynamic underwater channel modeling using a software based on ray-tracing algorithm
10.	Alatawi [12]	Experiment	Effect of salinity and turbidity in the Red Sea on white-LED-based UOWC.
11.	Kumar *et al.* [13]	Analytical and simulation	Improving the link performance of UOWC in terms of signal-to-noise ratio (SNR)

B. Geometrical Loss

Similar to Visible Light Communication (VLC), UOWC also use Laser Diodes (LDs) and Light-Emitting-Diodes (LEDs) as the potential light sources. In comparison to LED, LDs produce coherent and monochromatic light with a narrow spectral width, making them ideal for applications requiring precise wavelengths and focused intensity. They are, however, less energy-efficient, consume higher power, and have a shorter operational lifetime. In contrast, LEDs are highly energy-efficient, cost-effective, and have a longer operational lifetime. However, LEDs emit incoherent, polychromatic light over a broader range of wavelengths which may cause the Geometrical Loss (GL).

By definition, GL is defined as the ratio of the surface area of the receiver aperture to the surface area of the transmitter beam at the receiver [14, 15]. The GL for visible light communication link depends on the beam-width of the optical transmitter, the transmission length (z), and the divergence angle (θ). The diameter of the transmitter and receiver apertures are measurable parameters, typically provided by the manufacturer. The work in [3] has established the geometric loss ratio as follows:

$$GL\ ratio = \frac{4\pi(d_{rx}/2)^2}{\pi\left(z tan\frac{\theta_{tx}}{2}\right)^2} \quad (1)$$

where, d_{rx} is the receiver aperture surface, z is the distance between transmitter and receiver, and θ_{tx} is the viewing angle of the light source in rad. GL ratio is significant when the obtained ratio is less than 1, indicating the surface area size of the receiver aperture is too small to receive the transmitted light spot and consequently causes signal loss. Hence, the net received power is defined as:

$$P_{nett} = GL\,ratio \times P_{rx} \tag{2}$$

where P_{rx} is the received power.

C. Water Salinity

Salinity is defined as the concentration of dissolved salts. It is expressed in terms of Parts Per Thousand (PPT) or kilogram of salt in 1000 kilograms of water. The salinity in ocean water typically ranges from 31 to 37 Parts Per Thousand (PPT). In polar regions, salinity can drop below 30 ppt, while in the Antarctic, it usually maintains a level of around 34 ppt [7]. Two common methods are used to measure salinity. The first method measures salinity through Electrical Conductivity (EC) in micro-siemens per centimeter. The second method measures the quantity of salt particles in the solution, expressing it as total dissolved salts. Seawater typically contains common salts such as chlorides, sulfates, sodium carbonate, potassium carbonate, calcium carbonate, and magnesium carbonate. The typical ocean salinity is around 35 ppt as reported in [16], which means that 35 grams of material is dissolved in every 1000 grams of ocean water and can be expressed as 35 gm/L.

D. Luminous Efficiency

Luminous efficiency or luminosity, $V(\lambda)$ is the measure of the effectiveness of lights of different wavelengths defined for specific matching tasks. The value for $V(\lambda)$ for every visible wavelength from 380–770 nm has been estimated and tabulated in luminous efficacy tables [9]. Mathematically, $V(\lambda)$ refers to the measure of how effectively a light source produces visible light, $\emptyset$ (lumens) relative to the electrical power it consumes (watts), and it is typically expressed in lumens per watt (lm/W), with higher values indicating more efficient light production. The relation between $V(\lambda)$ and $\emptyset$ is given by:

$$\emptyset = V(\lambda) \times P_0 \times 683\text{lmW}^{-1} \tag{3}$$

where, P_0 is the radiation power emitted in Watts. From Eq. (3), light intensity, $\emptyset$ in lumen can be converted to power in watt:

$$P_0 = \emptyset / (V(\lambda) \times 683\text{lmW}^{-1}) \tag{4}$$

E. Beer-Lambert Law

Beer-Lambert law is the simplest method to model UOWC channel. Beer-Lambert law uses attenuation coefficient to describe the loss of light over a transmission length, z. Assuming the differential transmission loss is:

$$\frac{dI}{dz} = -cI \tag{5}$$

where, I is the power intensity on the volume of width dz, and c is the attenuation coefficient. The negative c is to describe the light is lost over the transmission link. Integrating Eq. (5) yields:

$$\int_{I_o}^{I} \frac{1}{I}\, dI = -c \int_0^z dz \tag{6}$$

$$\ln \frac{I}{I_o} = -cz \tag{7}$$

which when simplified, yields the Beers Law expression, where, I_o is the initial power intensity:

$$I = I_o e^{-cz} \tag{8}$$

The model is applicable for simple underwater environment where there is only absorption and no multiple scattering effects.

III. Methodology

A. Experimental Set up

An experimental set-up is established to study the effect on received optical signal as a function of varying transmission link for saline water channel. Due to the expensive and complex nature of open-water environments, a small glass chamber of dimensions of 0.6 meter by 0.3 meter by 0.15 meter is employed to emulate the water channel for our experiment. It should be noted that this experiment is focused on horizontal configuration of UOWC channel at which the transmission link from transmitter to receiver is measured horizontally.

Since the glass chamber is 60 cm long, the effective transmission link is only up to 50 cm. Measuring the light at 60 cm is not feasible because the light would be at the edge of the chamber, where there is no space to place the receiver. Therefore, we have omitted the consideration of temporal changes in salinity due to this short propagation distance (50 cm).

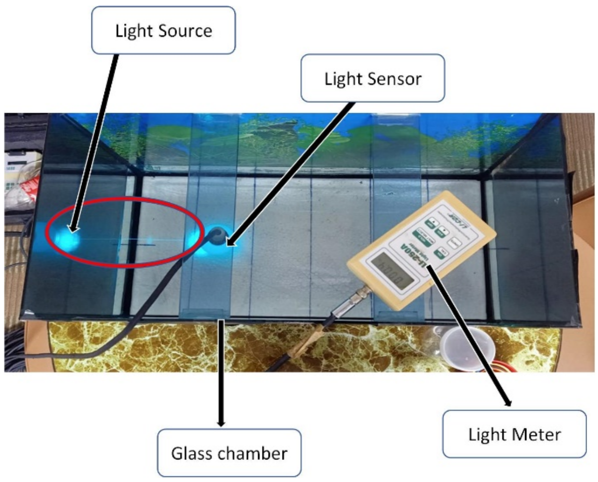

Fig. 1. Top view of the experimental set-up.

Three levels of salt concentration have been chosen for the saline water, including 31.53g/L, 35 gm/L, and 45 gm/L. The choice of these three-salt concentrations is based on the literature study that has been practiced by [7]. The experimental set-up comprising of transmitter, receiver, and light meter is shown in Fig. 1, and the experimental set-up parameters are summarized in Table

III. Different colors of Light-Emitting Diodes (LED) and laser diodes of wavelength range from 487–568 nm are used as transmitters. Green and blue light sources are selected due to the fact that seawater has a low-loss property in blue and green lights as shown in Fig. 2, the minimum absorption coefficient of pure seawater is within 450–550 nm for different light wavelengths extracted from [17].

TABLE III. SUMMARY OF EXPERIMENTAL SET UP PARAMETERS

Components	**Parameters**		
Transmitter light source	**Aparture diameter (mm)**	**Wave length (nm)**	**Viewing angle (rad)**
green LED	10	568	0.50
blue LED	10	487	0.50
Blue laser	6	488	0.001
Green laser	6	520	0.001
Channel scenario		**Channel salinity level (g/l)**	
Green LED light wave		31.53, 35, 45	
Blue LED light wave		31.53, 35, 45	
Green LED light wave		31.53, 35, 45	
Green laser light wave		31.53, 35, 45	
Receiver	**Aparture diameter (mm)**	**Spectral range of detection (nm)**	
Spherical underwater quantum sensor	61	400–700	

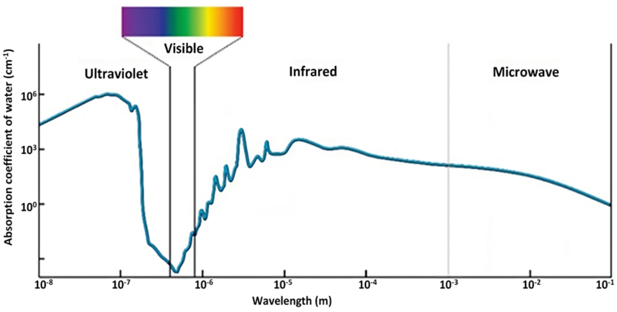

Fig. 2. Absorption coefficient of pure seawater [17].

On the other hand, LI-COR LI-193R Spherical Underwater Quantum Sensor is used as the receiver and the received light intensity is measured using LI-COR LI-250A light meter. This set of device is used because it accurately measures photon flux from all directions and gives an added dimension to underwater light intensity measurements [18].

The selected light source which served as the transmitter is attached outside the water tank and the receiver is placed inside the water tank to measure the intensity of the received light. The light source is placed outside the water tank because the light source is not waterproof as this is a low-cost basic model of UOWC. We acknowledge the effect of the changes in light refraction index as the light propagates between two mediums (glass and water) affected the accuracy of the received light intensity. However, this accuracy limitation does not cause changes in the measured intensity as we varied the experiment scenarios since all experimented scenarios are experiencing the same effect.

The flow diagram in Fig. 3 summarizes the overall steps undertaken for this work.

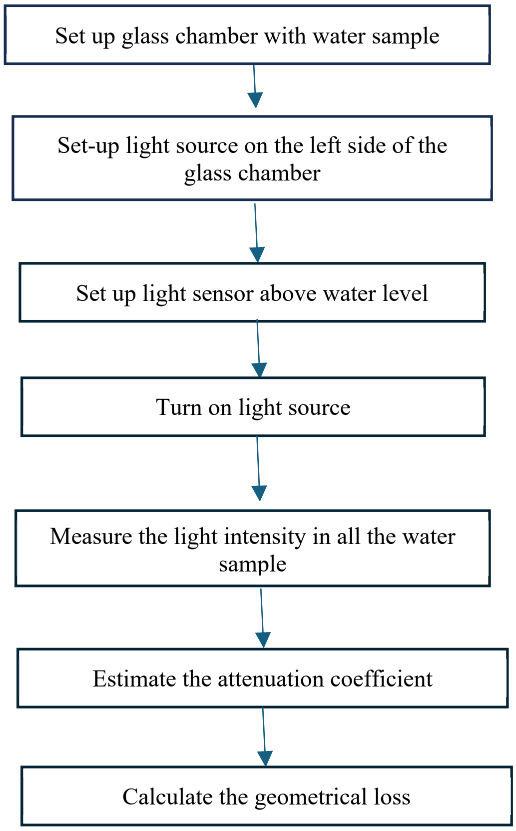

Fig. 3. Flow diagram of the overall methodology.

Figs. 4–7 shows the propagation of light using blue LED, blue laser, green LED, and green laser respectively, All the figures show the light is propagating in clear water condition. It should be noted that this experiment is conducted in the dark environment to make sure no external light source is being received by the receiver.

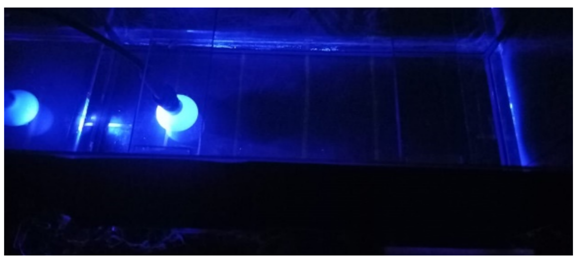

Fig. 4. Light propagation using blue LED as the light source.

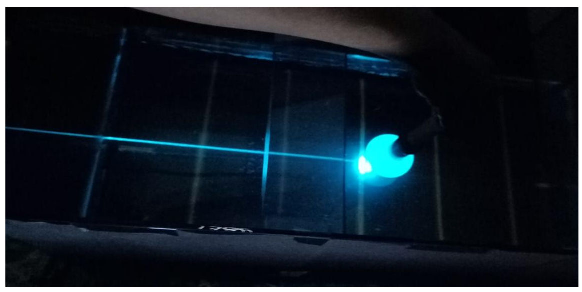

Fig. 5. Light propagation using blue laser as the light source.

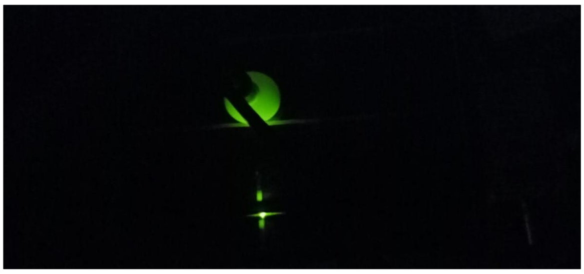

Fig. 6. Light propagation using green LED as the light source.

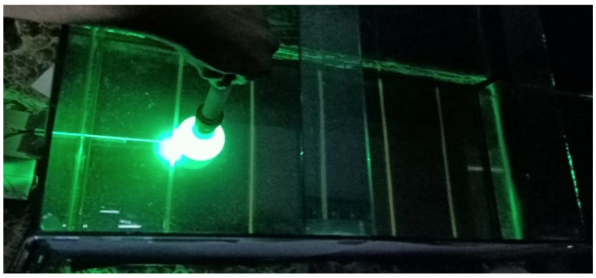

Fig. 7. Light propagation using green laser as the light source.

B. Calculation of Geometrical Loss Ratio

Using Eq. (2), GL ratio is calculated based on the experiment parameters listed in Table III. The valid range of GL ratio is less than 1.0 as has been explained in Section II, (Subsection *A*). Table IV tabulated the calculated GL ratio for all the light sources at varying distances of the transmission link. For consistency, any calculated GL ratio which results in more than 1.00 is set to 1.00, indicating that no GL is encountered by the respective light source. However, LED experienced a significant GL ratio as the transmission link increased because of the wider viewing angle compared to laser, as specified in Table III. The fact that coherent light produced by laser light compared to incoherent light produced by LED is enough to explain how the geometry of these two types of light will change, especially in underwater conditions. The effect might be significant if the distance is moved further.

TABLE IV. CALCULATED GL RATIO FOR ALL LIGHT SOURCE

Distance (meter)	Blue Laser	Green Laser	Blue LED	Green LED
0.0	1.00	1.00	1.00	1.00
0.1	1.00	1.00	1.00	1.00
0.2	1.00	1.00	1.00	1.00
0.3	1.00	1.00	0.63	0.63
0.4	1.00	1.00	0.35	0.36
0.5	1.00	1.00	0.22	0.23

C. Estimation of Attenuation Coefficient

Attenuation coefficient, c is estimated using Eq. (7) after obtaining the received light intensity, I, as the transmission link, z, gradually increases from 10 cm to 50 cm. I_o is the initial light intensity of incident light, measured at 0 cm. In order to estimate the value of c from the measured I, a natural logarithmic is applied to Eq. (8) resulting a linear equation as shown in Eq. (7). Then, the estimated value of c is obtained through linear curve fitting method as presented in Fig. 8. The slope of the linear equation deduced from the curve fitting gives the estimated value of c.

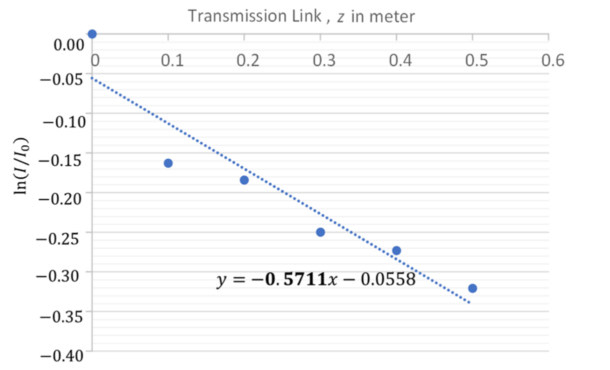

Fig. 8. Curve fitting method to estimate the attenuation coefficient (c = 0.5711 m^{-1}) for green laser propagates in 45 g/l of saline water.

IV. RESULTS AND DISCUSSIONS

A. Normalized Received Intensity

Fig. 9 shows the plots of normalized received light intensity in saline water with varying salt concentration of 31.53 g/l, 35 g/l, and 45 g/l using blue and green LED and laser diode respectively.

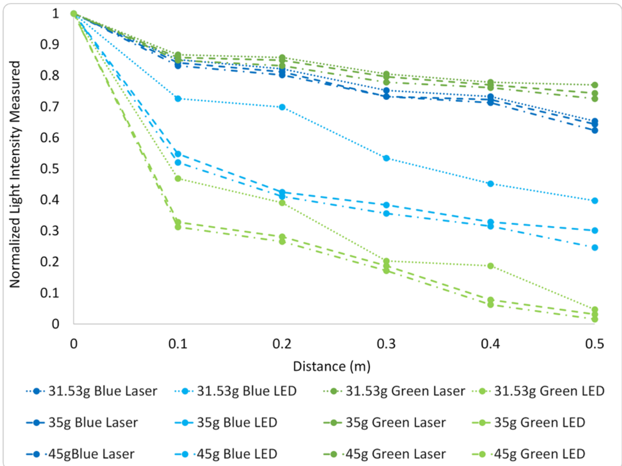

Fig. 9. Normalized received light intensity in saline water using all light sources.

For comparison, all the measured light intensities have been normalized by dividing the measured I with Io, the measured light intensity at zero distance. In common, it is observed that the received intensity of the optical signal emitted by all the light sources decreased as the underwater link length increased, in agreement with the stated Beer's law in Eq. (8). It is observed that the received light intensity is decreasing as the salt concentration of the UOWC channel is increasing, validating the hypothesis that the water salinity affects the performance of UOWC [7]. The salinity effect is significant when the salt concentration is reaching 45g/l.

Among all light sources, green laser light source emitted the strongest light intensity in all saline water conditions. The work in [19] claimed green light propagated in water with less attenuation but was sensitive to the temperature changes. On the contrary, the green LED light has shown the most deteriorating signal in this experiment, and it gets worse as the light propagates in saline water. This opposite effect between green LED and green laser light source despite the fact both are the same colour most probably because of the output power of the laser is much higher than LED. It can be seen in Fig. 6 that the light emitted by green LED is very dimmed as compared to other light sources.

B. Estimated Attenuation Coefficient

Table V tabulates the estimated attenuation coefficient, *c* that has been deduced from the curve fitting method.

TABLE V. ESTIMATED ATTENUATION COEFFICIENT (C)

Types of water	Light Sources			
	Blue LED	**Green LED**	**Green Laser**	**Blue Laser**
31.5g	1.8015	5.3444	0.4839	0.7618
35g	2.1804	6.2973	0.5352	0.7894
45g	2.4714	7.4455	0.5711	0.8322

The obtained *c* is consistent with the plots shown in Fig. 9. In summary, light waves from all light sources have shown similar effect towards the water salinity. The estimated *c* increases as the salt concentration in the water increases indicating the performance of UOWC is declining as the salinity of the water increases. We conclude that higher salinity levels can lead to increased attenuation of light waves in water.

This is primarily due to two main factors. Firstly, absorption: salts in water, particularly ions such as sodium and chloride, can absorb certain wavelengths of light. This absorption occurs as the light interacts with the charged particles in the water molecules and dissolved ions, causing the light energy to be converted into heat energy. The extent of absorption depends on the specific wavelengths of light and the concentration of dissolved salts in the water. Secondly. Secondly, scattering: salts and other dissolved particles in water can also cause scattering of light waves. Scattering occurs when light encounters irregularities or variations in the refractive index of the medium, causing the light to change direction and spread out in different directions. Higher salinity levels can increase the number of scattering events, leading to greater attenuation of light signals over longer distances. This justification is also in line with the results of the salinity study conducted in [7].

On the other hand, among all light sources, the green laser beam has consistently yielded the minimum value of c in different water types, likely due to its higher output power of 10 mW, compared to the 5 mW output of the blue laser. Consequently, the green laser possesses the ability to emit a robust and dependable light wave signal that remains resilient to attenuation effects.

C. Overall Performance Evaluation

Fig. 10 presents the received power in watt using green light sources (LED and laser) in 45 g/l of saline water. It should be noted that the received light measured from the experiments are in lux unit. The conversion from lux to lumen (lux = lumen/received area) unit is done prior to obtain the output power in watt using Eq. (4).

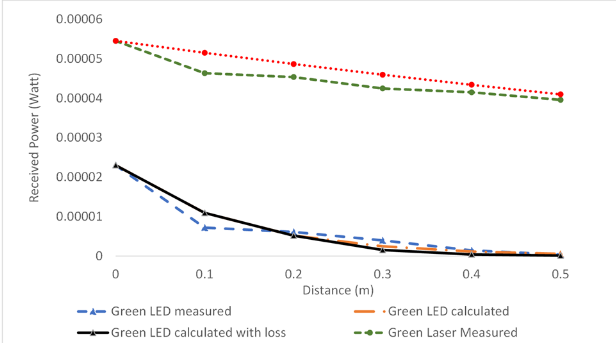

Fig. 10. Green LED light wave in 45g/l of saline water.

The plots compare the received power between measured, calculated, and calculated with loss from the green LED in 45 g/l of saline water, the worst-case scenario. In addition, the plots for the received power by green laser in the same water are also plotted for comparison purposes. In general, it is obvious that the green laser outperforms green LED since LEDs emit incoherent light with relatively low output power, while lasers emit coherent, high-intensity light with much higher output power. Therefore, laser diodes play an important role for long-distance and high-speed UOWC system [20].

The graphs for calculated power and calculated power considering the geometrical loss in Fig. 8 are computed using Eqs. (2–8) respectively. Fig. 7 shows the trend of the green LED plots is not consistently agreed with our hypothesis, at which the measured power must always be lower than the calculated power. The same trend of plots is also observed using blue LED irrespective of salinity level of the water.

The calculated power is supposed to be higher than the measured power because the calculated power only considers the attenuation loss as stated in Eq. (8). In contrast to the measured power which should have additional losses due to environmental effect such as ambient temperature (scintillation effects) and system design parameters, particularly the geometric loss [14]. It is anticipated that the slightly higher measured power is due to reflection phenomena. Some of the transmitted light in the experiment is reflected from all sides of the glass made water tank.

As a result, the reflected signals are carried all the way along to the end and received by the receiver together with the original transmitted light. Therefore, resulted in higher total received power and the aforementioned additional losses are not able to compensate for the received reflected signal. This unwanted phenomenon is also encountered by other work in Ref. [21]. In comparison to previous work in Ref. [3], it is interesting to note that this reflection phenomena have been minimized as the measured power is slightly higher than the calculated power only when the signal propagated between 0.2–0.4 m. This finding conforms to our technique to minimize the reflection by covering all sides of the glass tank into black colour and conducting the experiment in a dark environment in order to absorb the unwanted light is a promising technique.

However, it is interesting to note that the calculated received power by green laser is higher than the measured power, correctly following the hypothesis. In fact, the measured power becomes closer to the calculated power as the transmission link increases. It seems the reflection phenomenon has been completely minimized when the laser is used as the light source. The laser light wave also does not experience any geometrical loss because the calculated GL ratio is 1.00 as shown in Table V.

V. Conclusion

This work investigated the propagation of light waves in saline water for Underwater Optical Wireless Communication (UOWC). The study showed that the level of salinity concentration has an inverse effect on the UOWC channel. The salinity effect becomes significant when the salt concentration reaches 45 g/l. Among all light sources, the green laser light source emitted the strongest light intensity under all saline water conditions, demonstrating the green laser's ability to emit a robust and reliable light wave signal resilient to attenuation effects. Additionally, the measured power closely matched the calculated power, indicating that the reflection effect of unwanted signals was minimized by covering all sides of the water tank with black color.

However, a few limitations were identified in this work. Firstly, the setup transmission link was only up to 0.5 meters due to the small size of the water tank, whereas the expected range of UOWC technology can reach up to 90 meters. Secondly, this work only investigated the effect of water salinity on turbulence, which oversimplifies the real scenario since turbulence can also be influenced by other factors such as water currents, temperature gradients, and the presence of marine life.

Nevertheless, these limitations do not invalidate the study, as it is a proof-of-concept work still in its infancy and has a long way to go. Therefore, in the future, it is proposed to overcome these limitations by extending the transmission link up to 90 meters by conducting experiments in the open sea and considering other factors influencing turbulence, particularly temperature and water flow.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

W.H.W.H. designed the experiments, performed data interpretation, drafted the manuscript, and managed the manuscript submission process; N.B.S conducted the experiments, collected, and analyzed the data; F.J. contributed to the development of the theoretical framework and assisted with data interpretation; M.R.A. was responsible for the literature review and identified relevant previous studies; A.N.D. provided technical support and also contributed to the manuscript revision; Z.A.M. contextualized the current research within the existing body of work; S.M.I. provided critical revisions to enhance the intellectual content and coherence of the manuscript; all authors read and approved the final version of the manuscript.

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