



Experimental and Theoretical Investigation of the Effect of Salinity on Attenuation of 405 nm and 520 nm Laser Beams in Underwater wireless optical communication systems

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ABSTRACT

In this paper, the effect of salinity on laser signals was theoretically and experimentally examined. Here a comparative analysis of the two wavelengths in different saline water environments was conducted. Both the theoretical and experimental analyses were performed based on an underwater optical communication (UWOC) system. Based on the UWOC, 405 nm and 520 nm laser wavelengths were employed with an optical power of 10 mW and results under water [channel of varying salinity levels (10–80 g/L)] were investigated. The values of absorption and scattering coefficients for the sea environment were theoretically estimated in the visible wavelength region. The theoretical results showed that the 400–550 nm interval represents an optical transmission window for laser light, resulting in lower absorption coefficients. However, in high-salinity marine environments (high-concentration), the transmission windows across the visible region showed almost negligible effects due to increased scattering and absorption. This indicates that the scattering process in specific water types slightly decreases with increasing wavelength. This investigation is important to assess the suitability of (405 and 520) nm lasers as potential choices for efficient UWOC systems, particularly in dense or saline waters. It was found that power loss at maximum link distance increases with salinity level due to the effect of attenuation. As salinity level rises, the practical signal-to-noise ratio (SNR) decreases due to higher transmission losses caused by attenuation. Furthermore, the refractive index as a function of temperatures was theoretically estimated for 405 nm and 520 nm laser diodes. The results show that increasing the temperatures led to decreases in the estimated refractive index.

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1. INTRODUCTION

Underwater wireless communication (UWC) has emerged as a cornerstone of modern maritime technology. It is considered as a potential for revolutionize applications such as underwater exploration, remotely operated vehicles (ROVs), and enhanced diver communication, nowadays underwater communication is Also essential in different applications such as industries, marine research, telecommunications, security, and environmental protection. [1]. The traditional UWC system mainly

depends on acoustic waves (AW) which has been proved in transmitting data for long range with low attenuation property. However, AW suffers from a low data rate limitation due to the low modulation bandwidth and low propagation speed leading to a latency of 0.67s/km [2][3]. Compared to AC, underwater radio frequency (RF) suffers from a high signal attenuation due to the low conductivity of electromagnetic waves in water, which leads to a severely limited transmission distance and decay. Thus, RF is considered unsuitable for UWC applications [3]. Optical communication technologies offer promising alternatives through underwater wireless optical communication (UWOC) system due to high data rates and robust security, with lower power consumption compared to traditional acoustic and/or RF systems. Yet, optical systems are hindered by light absorption, scattering, and interference phenomena. Moreover, UWOC require energy constraints, line-of-sight (LOS) alignment and clear water conditions to achieve effective deployment [1,4,5]. Based on UWOC, Light-emitting diodes (LEDs) or Laser diodes (LDs) are usually adopted as a visible light source for these systems. Compared to the LEDs, LDs have stronger penetration, longer transmission distance, and higher transmission rate underwater, making them a better choice for underwater optical wireless communication [6]. However, many challenges associated with UWOC systems is the requirement of LOS between the moving transmitter and receiver [7]. Furthermore, the percentage of disturbances due to the concentration of dissolved salts such as NaCl, MgCl, Na₂SO, and KCl lead to enhance both the absorption and the scattering processes in seawater [8]. The attenuating of light and random variations of refractive index by seawater related to many parameters. These parameters include wavelength of light, water's quality, temperature, salinity, and pressure, and suspended particles that contained in the seawater [9-13]. However experimental results showed that using pulse position modulation (PPM) based on a 450 nm LD and a multi-pixel photon counter (MPPC) receiver can achieve data rate of 5 Mbps at 46 m link in UWOC system. Later, using a 520 nm LD in UWOC system, data rate of 500 Mbps was experimentally achieved at 100m link by J. Wang et al.[14]. Furthermore, the blue-green wavelengths (420–532 nm) give a low attenuation window as mentioned by Sullivan and Dimtle in 1963, where the attenuation increases gradually towards the red wavelengths. Therefore, we can perceive the deeper clear ocean as blue because the other wavelengths are more strongly attenuated than the blue wavelength[15-16].

2. METHOD

2.1 Blue and Green Laser Transmission in Aquatic Medium

Compared to other regions of the electromagnetic spectrum, the visible light spectrum is less absorbed in seawater especially in the blue-green region [17, 18]. Based on water type and/or environmental obstacles, high-speed communications using blue-green wavelengths can be achieved [18, 19]. The optical properties of ocean water can be divided into two categories: apparent optical properties and inherent optical properties [20]. inherent properties can be described as optical parameters that dependent solely on the medium itself, such as the composition of ocean water, rather than the properties of the light source [21]. Underwater signal attenuation is affected by the size of scattering particles and the level of absorption, with both phenomena being wavelength and particles size dependent [19]. The energy loss of light can be generally evaluated by absorption coefficient $A(\lambda)$ and scattering coefficient $S(\lambda)$, therefore, the attenuation coefficient $\tau(\lambda)$ defined as [27,29]:

$$c(\lambda) = \alpha(\lambda) + b(\lambda) \dots \dots \dots (1)$$

There are many types of substances responsible for seawater properties. These substances include phytoplankton, non-chlorophyllous biological particles, dissolved organic matter and/or salt concentration. However, the values of $A(\lambda)$ and $S(\lambda)$ depend on water type and wavelength λ . For simplicity the values of chlorophyll concentration C are used to characterize different water types. Therefore, the values of $A(\lambda)$ and $b(\lambda)$ can be expressed as a function of the wavelength and concentration [22]:

$$\alpha(\lambda) = [a_w(\lambda) + 0.06a_c(\lambda)C^{0.65}][1 + 0.2 e^{(-0.014(\lambda-440))}] \dots \dots \dots (2)$$

On the other hand, scattering changes direction of the light path after interacting with suspended particles [17,20,22],

$$b(\lambda) = 0.30 \frac{550}{\lambda} C^{0.65} \dots \dots \dots (3)$$

Wave speed always varies with the optical characteristics of the medium. All the materials are categorized according to their optical refractive index (n), which is their capacity to slow down waves [23]. In addition to the attenuation factor, the UWOC is affected directly by index of refractive change due to the fluctuations in temperature and dissolved organic matter and/or salt concentration. Based on Cauchy formula, n is a function of temperature and wavelength as presented in equation 4 [24,25]:

$$n(\lambda, t) = A(t) + \frac{B(t)}{\lambda^2} + \frac{C(t)}{\lambda^4} + \frac{D(t)}{\lambda^6} \dots \dots \dots (4)$$

Based on this equation, the Cauchy coefficients **A(t)**, **B(t)**, **C(t)**, and **D(t)** have been approximated by polynomial of three-degree equations as illustrated in equations (5-8) [23]:

$$A(t) = 1.3208 - 1.2325 \times 10^{-5}t - 1.8674 \times 10^{-6}t^2 + 5.0233 \times 10^{-9}t^3 \dots \dots \dots (5)$$

$$B(t) = 5208.2413 - 0.5179t - 2.284 \times 10^{-2}t^2 + 6.9608 \times 10^{-5}t^3 \dots \dots \dots (6)$$

$$C(t) = -2.5551 \times 10^8 - 18341.336t - 917.2319t^2 + 2.7729t^3 \dots \dots \dots (7)$$

$$D(t) = 9.3495 + 1.7855 \times 10^{-3}t + 3.6733 \times 10^{-5}t^2 - 1.2932 \times 10^{-7}t^3 \dots \dots \dots (8)$$

For further characterization of transmitted laser signal, propagation loss factor as a function of wavelength (λ) and transmitted link R given by Beer-Lambert law based on input powers $P_{in}(\lambda)$ and output power $P_{out}(\lambda, R)$ explain by equation-(9) [26,27,28].

$$P_{out}(\lambda, R) = P_{in}(\lambda) e^{-\alpha(\lambda)R} \dots \dots \dots (9)$$

Furthermore, the attenuation coefficient $\alpha(\lambda)$ can be written as [28].

$$\alpha(\lambda) = \frac{1}{R} \ln \frac{P_{out}(\lambda, r)}{P_{in}(\lambda)} \dots \dots \dots (10)$$

Underwater light attenuation is the reduction of beam intensity due to absorption and scattering by dissolved contaminants in water, including organic and inorganic particles [29]. Therefore, based on the on input P_{in} and measured output P_{out} powers of the LDs light source, the attenuation loss parameter can be expressed by [30]:

$$\text{Attenuation loss} = 10 \log \frac{P_{in}}{P_{out}} \dots \dots \dots (11)$$

The signal quality of the UWOC performance refers to the ability to recognize the signals received as valid information while ignoring any unwanted signals. However, signal-to-noise ratio (SNR) of UWOC based on power units is the proportion of signal power to noise power [19,31]. As written in the equation 13, the P_n is the average noise power, and P_s is the average signal power [32].

$$\text{SNR} = 10 \log \frac{P_s}{P_n} \dots \dots \dots (13).$$

2.2 Experimental Setup of UWOC System

The experimental was set up to investigate the behavior of optical signals in terms of received power using 405 nm and 520 nm LDs (model/Ziqqucu). Both LDs had an output power of 10 mW and the transmitted signals were examined using Pulse Width Modulation (PWM). The received power in water medium that represents a UWOC channel was tested at different turbidity levels. The UWOC system included transmitter and receiver units, as well as a rectangular glass tank with dimensions of 1 m $\times$ 0.2 m $\times$ 0.25 m serving as the water channel. The tank was covered with a black cage to reduce the impact of ambient photons from reflections or background scattering. To modulate the laser signals based on the uploaded code, the Arduino Uno microcontroller was connected to a personal computer (PC) and used as an optical transmitter.

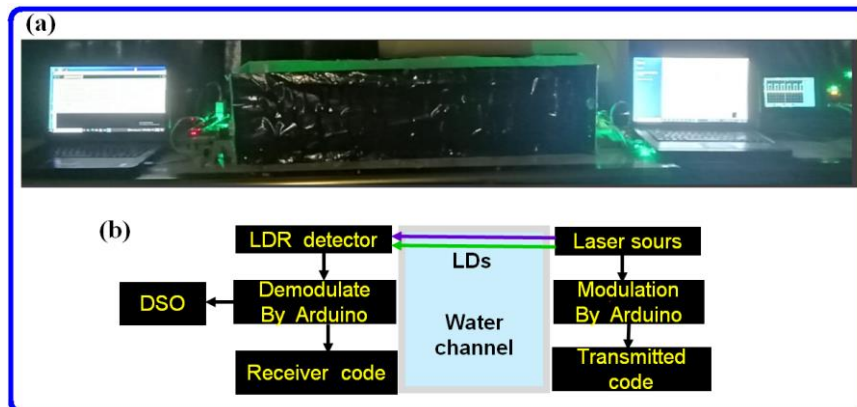


Figure 1. Experimental setup of UWOC demonstrations: in the laboratory environment (a). General diagram of how the UWOC system works and processes (b).

To ensure accurate and effective control of laser operation, a MOSFET circuit was attached to the Arduino Uno. Figure 1 shows the experimental setup of UWOC system in this work, based on PWM for diode lasers. The incoming optical signals passing through the water channel were detected on the receiver side by a photoresistor or light-dependent resistor (LDR) Model GL55228. Table 1 shows the detailed specifications

information of the components that are used in the experimental setup, where (a) representst the laser diode, (b) Mosfet, (c) LDR.

Table 1. The detailed specifications of the components used in the experimental setup, where (a) represent the Arduino microcontroller, (b) Mosfet, (c) laser diode.

(a)	
Specifications information	Values
A microcontroller	ATmega328p
Voltage of operation	5 volt
Voltage input	7-12volt
Voltage input (limit)	6-20volt
Digital I/O pins	Six
for PMM	
digital I/O Pins	
analog input Pins	
Dc current per I/O pin	14 (which 6 provide PMM)
3.3 v Usingflash Memory	6 six
	20 mA
	50 mA
SRAM	
EEPROM	32 KB(ATmga 328p) of which
Clock Speed	0.5 kb useds by boat loader
LED-BULTIN	2 KB (ATmega328p)
length	1 kb (ATmga 328p)
	16 MegaHz
	13
	68.6 mm
(b)	
Specification	Value
Weight	10g
voltage	3.3-5Volt.
Port	digital Levels.
output	0-24V.
Voltage	
output	<5A.
Current	
platForm	arduino , mCu, and aRM
Output Pwm	original IRF520 Power
	moS
(c)	
Specification	Value
Model	Q-LINE
Wavelengths	405 nm
Output Power	10mW
Operating Voltage	3-5 Volt
Size	Length 35mm and
Operating	diameter 12mm
Temperature	+10 C + 40 C
Laser shape	Line
Lens	Plastic
Dimensions	12*12*35 mm
Wavelength	520nm
Working voltage	3-5V
Diameter	6 mm
Length	12 mm
Focal length	Adjustable
Optical single	Line crossover pattern

The demodulation procedure was carried out using an LDR, which acted as the optical receiver by detecting and covertng the incoming laser light into electrical signals. A second personal computer (PC2) then received and analyzed the resulting electrical signal, In parallel, a light power meter was used to monitor the received light power in order to assess the link's performance. A Digital Storage Oscilloscope (DSO), Model

UTD2102CEL, was also connected to the receiver system to view and record the waveform of the received signal in real time. In the water channel, the intensity of the laser power was measured at different salinity levels and varying link distances. To simulate different saline channels, water with various salt concentrations of (10 - 80) g/L was used. for each channel, received power at different link distances was observed. In this scenario, point-to-point Line-of-Sight (LOS) configuration between the transmitter and receiver was used with zero slope angles.[15,33].

3. RESULTS AND DISCUSSION

Figure 2 (a,b) presents the analytical values of absorption (A) and scattering (S) coefficients across various wavelengths. It clearly demonstrates that these optical properties depend both the wavelength used and the type of marine environment. It was observed that Pure Sea water exhibits the lowest absorption and scattering coefficients compared to Clean Ocean, and Coastal Ocean waters. This result is attributed to the lower concentrations of phytoplankton, non-chlorophyllous biological or terrestrial particles, and dissolved organic matter in pure seawater [35, 37]. At the wavelength of 405 nm, the absorption coefficient in Pure Seawater was 0.01932 m^{-1} , and the scattering coefficient was 0.01544 m^{-1} . In contrast, these values increased significantly in coastal ocean water, reaching approximately 0.06565 m^{-1} for absorption and 0.47371 m^{-1} for scattering. At 520 nm, the absorption coefficient in Pure Seawater was 0.02974 m^{-1} , with a scattering coefficient of 0.01236 m^{-1} . In Coastal Ocean water, these values rose to around 0.07234 m^{-1} for absorption and 0.37896 m^{-1} for scattering. it is evident that water type has a more significant impact on the scattering coefficient than on the absorption coefficient. Additionally, scattering process in a specific water type decreases with increasing wavelength, while absorption is influenced by the presence of humic acids, fulvic acids, and chlorophyll [35, 37]. These findings highlight the importance of wavelength selection based on the marine environment type, particularly for applications such as underwater optical communications and environmental sensing.

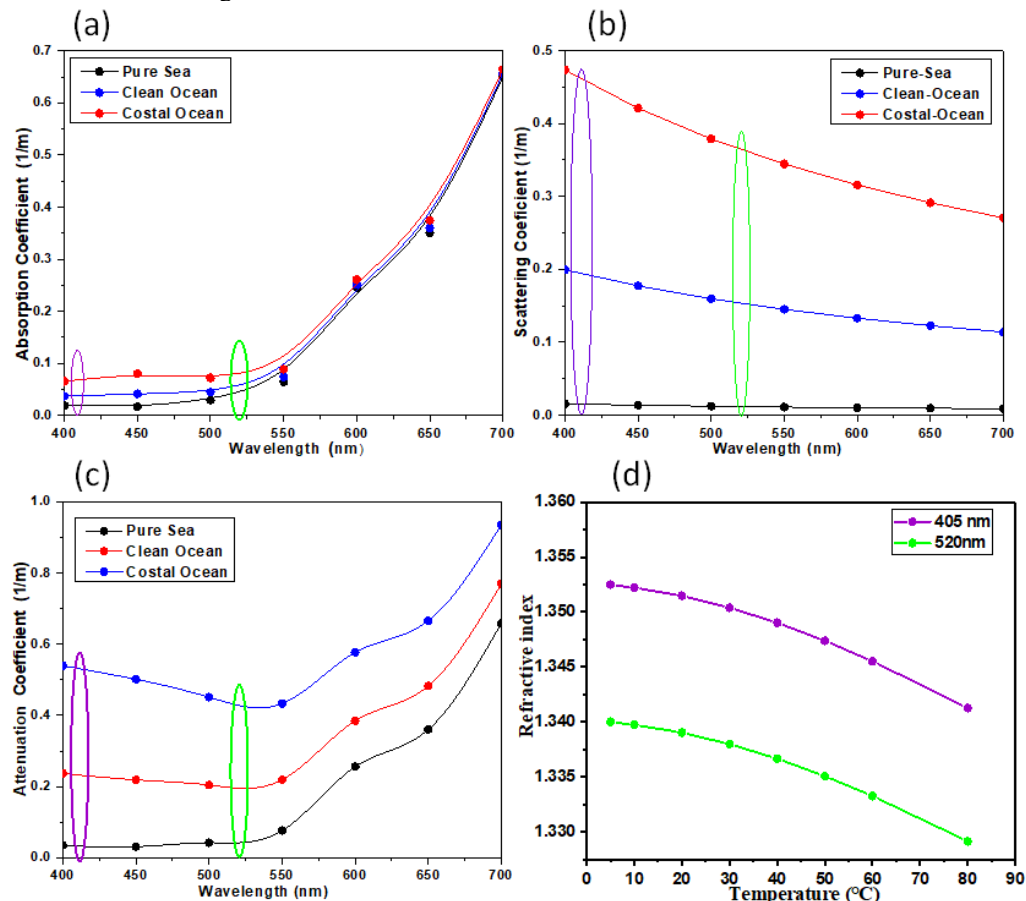


Figure 2. Analytical values of: (a) Absorption coefficients ($A_{(\lambda)}$), (b) Scattering coefficients ($S_{(\lambda)}$), and (c) the Attenuation coefficient ($\tau_{(\lambda)}$). Theoretical refractive index as function of temperature (d).

For instance, using a wavelength of 520 nm is advantageous in clear water to minimize optical losses, whereas wavelengths longer than 520 nm may require greater consideration in turbid or coastal environments. Figure (2c) shows that the attenuation coefficients depend on both the marine environment (water type) and the wavelength. At a wavelength of 405 nm, the attenuation coefficient in the pure-sea environment was the lowest at 0.03476 m^{-1} , while it reached 0.23681 m^{-1} in clean-ocean water, and 0.53936 m^{-1} in the coastal-oceanwater. Similarly, at 520 nm, the attenuation coefficient values were 0.04209 m^{-1} for pure-sea, 0.20437 m^{-1} for clean-ocean, and 0.4513 m^{-1} for coastal-ocean. These results highlight the impact of both wavelength and marine environment on attenuation behavior. In general, the attenuation coefficient increases with decreasing wavelength, and the coastal-ocean environment consistently shows higher attenuation than clean-ocean and pure-sea across all wavelengths. The increased attenuation in clean and coastal waters compared to pure seawater can be primarily attributed to the higher concentrations of suspended particles, dissolved organic matter, and other impurities. These constituents contribute to greater scattering and absorption of light, especially at shorter wavelengths [34,36]. Variations in refractive index are caused by changes in the water properties. Figure 2 (d) shows how seawater's refractive index changes with temperature at two different wavelengths, 405 nm and 520 nm, based on Equations 4-9. The refractive index steadily decreases as the temperature a rise. The 405 nm wavelength exhibits a higher refractive index (n) than 520 nm and both curves decrease with increasing temperature. Temperature variations affect water density, which in turn influences the speed of light through the medium and causes changes in the refractive index, where the temperature is higher. According to Snell's Law, these variations affect the propagation of light between different media [39].

The theoretical values of received optical power under different marine environments are plotted in Figure 3 for wavelengths of 405 nm and 520 nm as a function of underwater range. As can be seen, the received power decreases by increasing underwater distance for both wavelengths and across all environments. At a wavelength of 405 nm, the theoretically received power at a distance of 10 cm reached to 6.89488 mW, 5.34049 mW, and 4.00086 mW in pure-sea, coastal-ocean and clean-ocean respectively. As the range increased to 100 cm, the received power declined to 1.26633 mW, 0.80166 mW, and 0.34407 mW, in pure-sea, clean-ocean and coastal-ocean respectively. At a wavelength of 520 nm, a similar trend was observed, but with slightly higher initial values. At 10 cm, the received power was approximately 8.69258 mW in pure-sea, 6.84698 mW in clean-ocean, and 5.28666 mW in coastal-ocean waters.

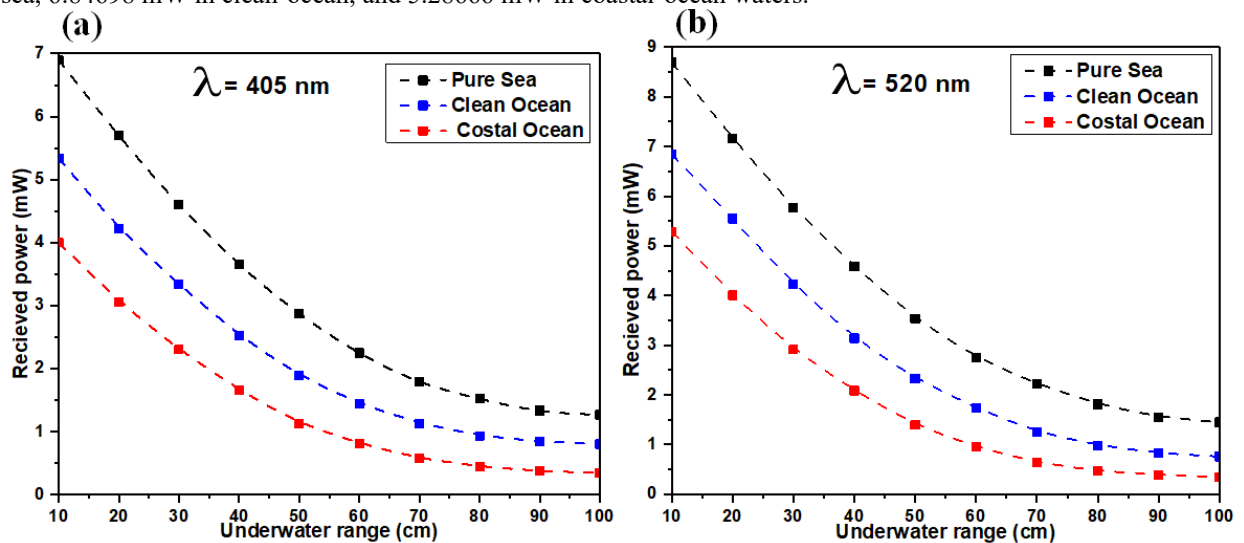


Figure 3. Analytical results of received optical power estimated for Pure Sea, Clean, and Costal Ocean, at 405 nm LDs (a) and 520 nm LDs (b).

When the range extended to 100 cm, the received power dropped to 1.4503 mW, 0.75607 mW, and 0.35027 mW, in pure-seawater, clean-ocean and coastal-ocean respectively. These results confirm that both the marine environment and the underwater distance significantly influence the received optical power. The higher received power in pure-sea water is attributed to its low attenuation coefficient, resulting from minimal suspended particles and lower absorption and scattering effects. In contrast, clean and especially coastal waters contain more impurities and suspended materials, leading to higher absorption and scattering, which significantly reduces transmitted power over distance. Therefore, as the underwater range increases, the signal undergoes greater attenuation in turbid waters, causing a sharper decline in received power. Figure 4 shows the combined effect of salinity concentration and water channel length on the received power. The

results indicate that the received power decreases with increasing salinity concentration and underwater distance, and this decrease is more pronounced at shorter wavelengths. At a distance of 10 cm, the received power was 8.833mW for 520 nm in tap water, while it dropped to 6.4933 mW for 405 nm under the same condition. As the salinity increased to 80 g/L, the received power at 10 cm decreased to 3.784 mW at 520 nm and even lower to 3.107 at 405 nm. At a longer distance of 100 cm, the received power at 520 nm dropped to 2.0104 mW in tap water and to 0.04824 mW at 80 g/L salinity. These results demonstrate that higher salinity and shorter wavelengths (such as 405 nm) both contribute to increased signal attenuation in underwater environments due to enhanced absorption and scattering caused by dissolved salts and suspended particles in the water.[15]

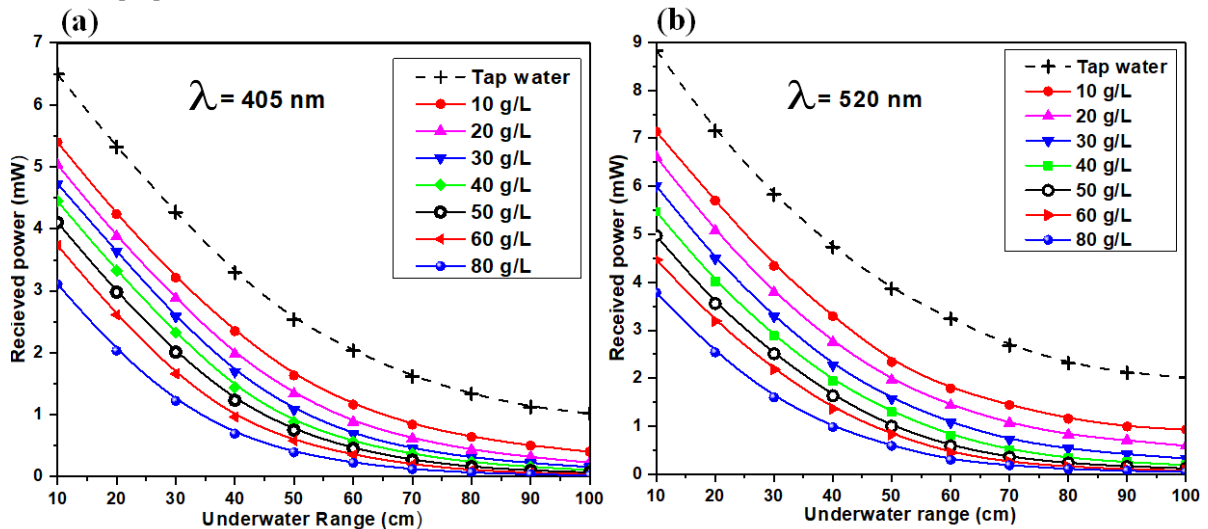


Figure 4. Experimental variation of received optical power with water channel length and salinity concentration: (a) 405 nm LDs and (b) 520 nm LDs.

Higher salt concentrations increase refractive index variations and particle density, leading to stronger interaction between the optical signal and the medium, which results in greater energy loss. Figure 5 illustrated the distribution and mean values of the attenuation loss. Here the attenuation loss was evaluated based on the received optical power using Equation (12).

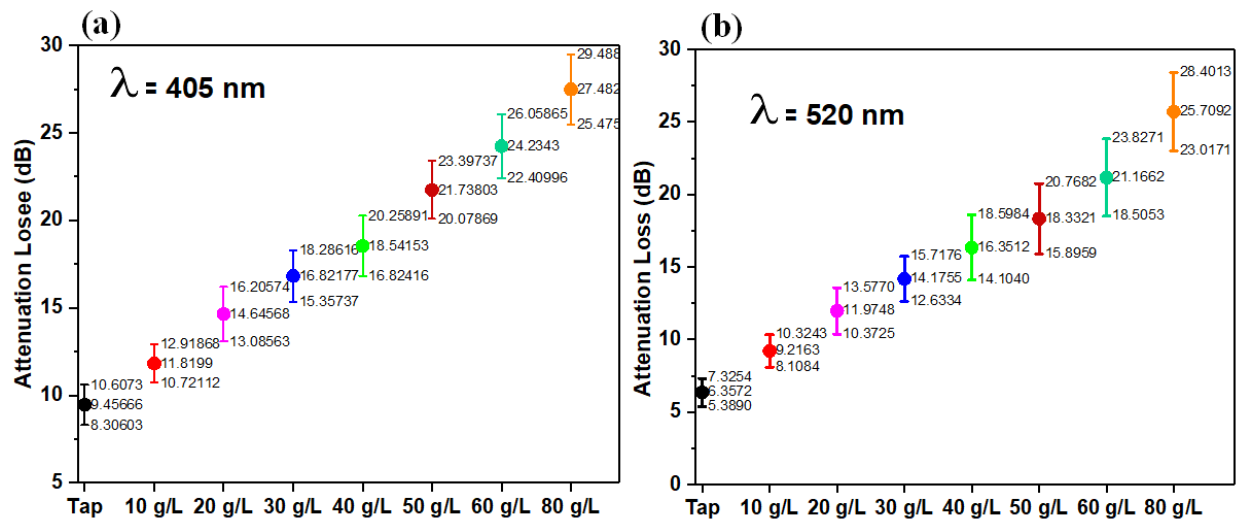


Figure 5. Attenuation loss distribution at different water salinity levels measured for: (a) 405 nm LDs and (b) 520 nm LDs.

The data clearly indicate that attenuation increases proportionally with salinity, and shorter wavelengths. And At a 1-meter underwater distance, the mean attenuation in tap water was 9.457 dB, increasing significantly to

27.482 dB at a salinity level of 80 g/L for the 405 nm LDs wavelength. For the 520 nm LD wavelength, the mean attenuation was 6.357 in tap water and it increased to 25.709 dB at 80g/L salinity, This rise in attenuation is primarily due to the scattering of light by saline particles, which weakens the received signal and reduces the efficiency of the UWOC system [33]. A comparison between the two wavelengths shows that attenuation was higher at 405 nm across all salinity levels. This is attributed to the fact that shorter wavelengths, such as 405 nm, are more susceptible to scattering and absorption in saline and impure water environments. In contrast, the 520 nm wavelength exhibited better transmission performance with relatively lower attenuation, making it more suitable for turbid or saline conditions. This is because longer wavelengths scatter less due to the reduced effect of Rayleigh scattering with increasing wavelength, thereby improving optical transmission and system efficiency in saline or turbid environments. The error bars indicate variability in the measurement of received signal power based on pulse width modulation, which could lead to variation in measured values of the attenuation. In addition to the impact of the salinity and impurities on UWOC performance, poorly received signals may also be attributed to other factors such as refractive index variations and water deep (temperature) [33].

Figure 6 illustrates the SNR as a function of underwater transmission range and varying salt concentrations for two wavelengths: 520 nm and 405 nm. Based on Equation (13), the SNR for both LDs wavelengths decreases as the underwater distance increases, with a more significant decline observed at higher salinity levels.

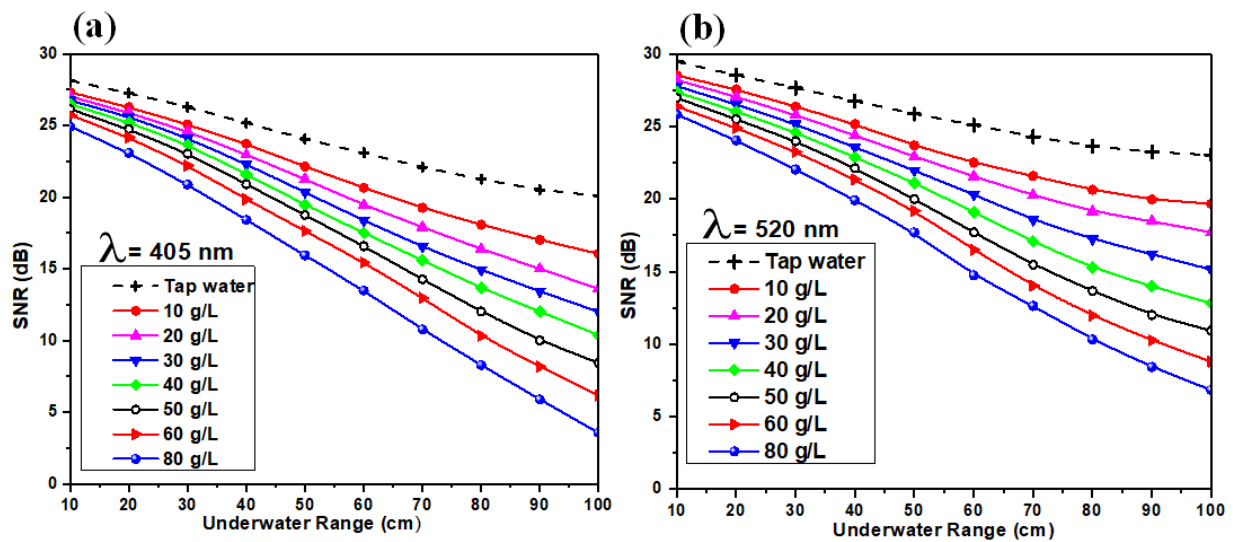


Figure 6. (SNR) under different salinity concentration in the water channel for: (a) 405 nm LDs and (b) 520 nm LDs.

For 520 nm, in tap water, the SNR decreased from 29.461 dB to 23.0328 dB at the receiver over a 1-meter range, primarily due to absorption effects in Tapwater. When the salinity was increased to 40 g/L, the SNR dropped further from 27.378 dB to 12.818 dB at the receiver. At 80 g/L, the SNR was reduced to 6.834 dB indicating a strong degradation in signal quality. Similarly, at 405 nm, the initial SNR in tap water was higher but showed a steeper decline with increasing salinity. For instance, at 40 g/L, the SNR fell from approximately 26.479 dB to 10.3873 dB, and further decreased to below 3.5736 dB at 80 g/L. The reduction in SNR at the receiver in the presence of salt indicates a strong effect of salinity on optical signal transmission, primarily due to attenuation dominated by the scattering of light by saline solutions, particularly at shorter wavelengths such as 405 nm.[38].

In figure 7 the effect of salinity on UWOC performance was evaluated by tracking and recording the received signal's waveform using an oscilloscope. The oscilloscopes images illustrate how varying salinity concentration affects the optical signals transmitted by both green and blue LDs through the underwater channel. In tap water, the waveform is distinct and clear, with the green LD showing stronger transmission compared to the violet LD, indicating efficient signal propagation, while minor amplitude variations are modest variations are likely caused by inherent system noise, the crisp and consistent peaks reflect minimal attenuation and distortion. As salinity increases, the waveform to becomes less clear, showing slight attenuation due to light absorption and scattering. At a salinity of 40 g/L, further absorption and dispersion are evident, as reflected by the reduced signal amplitude. Consequently, transmission quality noticeably deteriorates, and the waveform edges become uneven at high salinity level. At the highest salinity

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concentrations (80g/L), the waveform is extremely weak, and the amplitude nearly vanishes, effectively eliminating the signal intensity. This significant signal dispersion at the maximum tested transmission range is primarily due to attenuation caused by scattering processes [39].

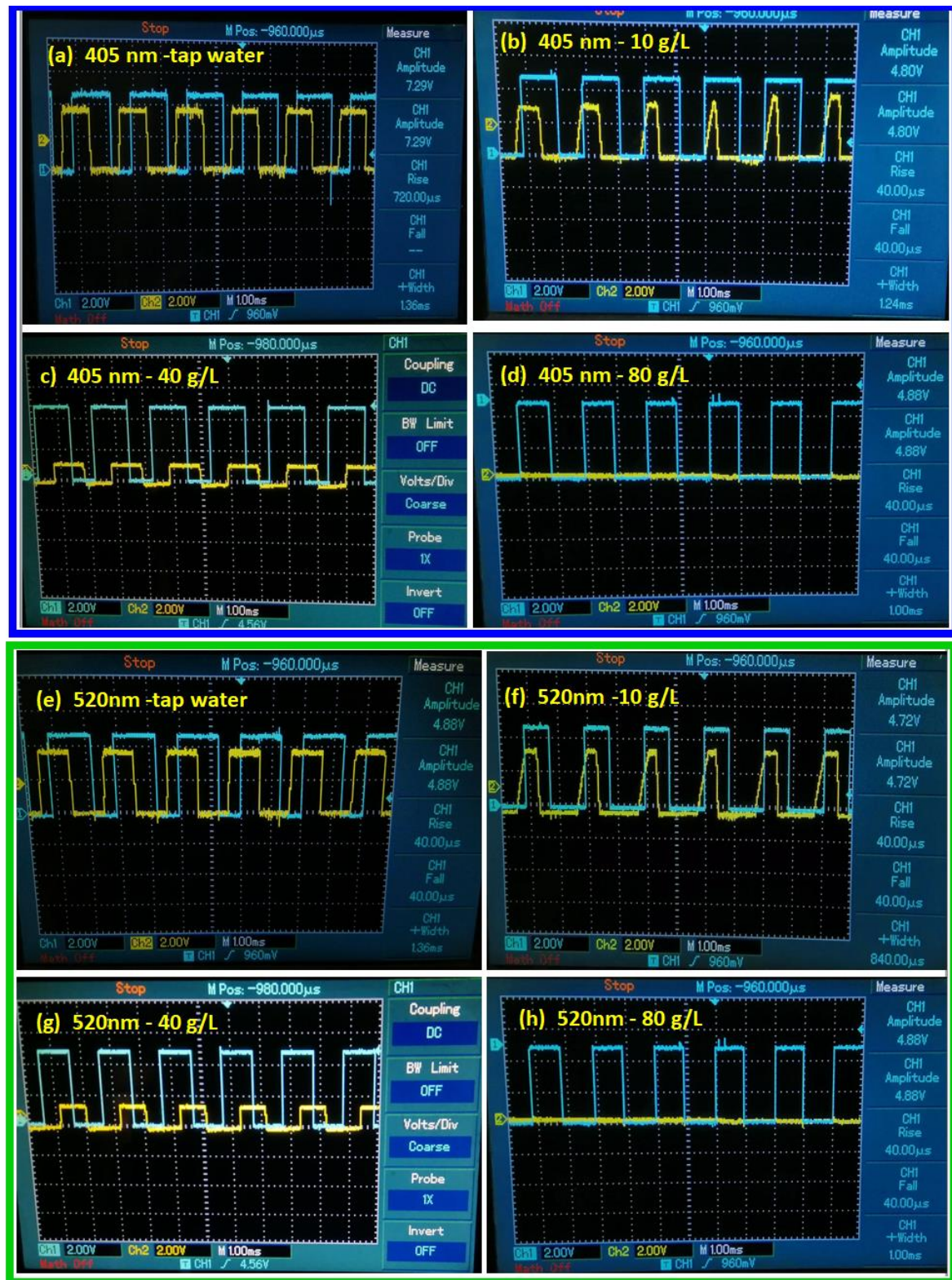


Figure 7. Oscilloscope images of laser waves at wavelengths of 405 nm and 520 nm under different salinity concentrations.

4. CONCLUSION

The UWOC system was designed using two visible laser wavelengths, 520 nm (green) and 405 nm (blue), with optical powers of 10mW for transmission. Different types of water channels, including tap water and saline water with varying salt concentrations, were used to evaluate the performance of the laboratory UWOC system. Analytical results of absorption and scattering coefficients were estimated as functions of wavelength. The absorption coefficient exhibited minor variation compared to the scattering coefficient across wavelengths. It was observed that scattering effects are more pronounced at shorter wavelength, particularly at 405 nm, and tend to decrease as the wavelength increases to 520 nm. This behavior underscores the importance of wavelength selection, suggesting that 520 nm lasers offer better performance for underwater communication. The impact of salinity on signal degradation was evident at a short underwater distance of 10 cm. The optical power received decreased from 8.833 mW in tap water to 3.784 mW in highly saline water with a salt concentration of 80 g/L for green laser, while it decreased from 6.493 mW to 3.107 for blue laser. Additionally, theoretical and experimental results showed similar trends in power loss across all water types. The SNR also showed a marked decline with increasing salinity. At a 1-meter range, SNR dropped from 23.032 dB in tap water to 6.834 dB in saline water at 80 g/L for the green laser, while it decreased from 20.1001 dB to 3.5736 dB at 405 nm wavelength. However, the reduction in SNR at the receiver in saline water is primarily due to attenuation dominated by the scattering of light by saline solutions. It was also noted that the performance of UWOC could be affected by other parameters such as the refractive index, which depends on various factors including wavelength, temperatures and the optical density of the medium [39].

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