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Salinity Effect on Red-light laser transmission based on Underwater Wireless Optical Communication system.

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ABSTRACT

In this work, the behavior of 650 nm red laser signals based on underwater wireless optical communication system was experimentally and theoretically investigated in different salinity levels (0–60)g/L. The values of absorption and scattering coefficients for marine environment have been theoretically estimated based on visible wavelength region. The theoretical results showed that the (400-550) nm intervals consider high windows for the laser light leading to lower absorption coefficients. However, at high salinity marine environment (Coastal-ocean), the light windows of water showed almost non-existent or negligible effects for the entire visible region. This finding indicated that the scattering process at specific water type slightly decreases with increasing the wavelength. This investigation is important to select 650 nm red lasers as best visible widow of efficient UWOC system especially for high impurity (dense) and/or saline water. It was found that the amount of losses in power at maximum link decrease with increasing salt concentration due to the negative effect of salinity on underwater signal transmission. When the salt concentration increased the practical signal-to-noise ratio value decreases due to large increasing in the transmission losses due to negative effect of the attenuation onto transmitted signal. Furthermore, the experimental refraction index based on different water channels and temperatures was measured and compared with and theoretical estimation. This finding shows that increases the salt concentrations led to increasing the index, while it decreases with increasing the temperatures.

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1. INTRODUCTION

Underwater Wireless Optical Communication (UWOC) has been identified as an innovative technology for reliable high-throughput data transmission for underwater environment. This technique, which employs optical signals, usually formatted as laser beams, to transmit information over water. When it comes to the different light sources, semiconductor lasers are interest in this regard due to their efficiency, small size, and wavelength precision [1]. The UVOC systems can be affected considerably by significant variables such as the salinity of the aquatic medium and therefore change the interaction of these laser signals with an aquatic medium and lead to a decrease in the quality and reliability of transmitted signals [2]. Salinity, which refers to the amount of salt dissolved in water, is an important measure of the health of underwater ecosystems. It changes the physical and optical properties of water-dynamics like density, refractive index and absorption and scattering of light. In turn, these properties strongly impact on the dynamics of optical signals [3]. When light passes through water it interacts with particles, ions and other impurities that absorb or scatter the light. The optical signals interactions have salinity dependent behavior [4-6]. In addition to the underwater environment, UWOC systems performance is dependent directly on the optical widow of the laser beam. However, semiconductor lasers are especially appropriate for UWOC applications due to their high modulation bandwidth and good line width property enhancement. Lasers with wavelengths in the red (on the order of 650 nm), are particularly suitable because they show a much lower absorption coefficient compared to other wavelengths [6,7]. However, red-light lasers also are not immune to the salinity effects. At this wavelength, scattering and absorption coefficients of water depend also on ionic composition and particulate matter linked to salinity [8,9]. Therefore, it was necessary to study and detect the impacts of salinity on the propagation of the red-light laser to enhance the efficacy of UWOC systems. Dissolved ions including sodium (Na^{+1}), chloride (Cl^{-1}), magnesium (Mg^{+2}) and sulfate (SO_4^{-2}) present in saline water provide additional electrical charges and increase the effective conductivity of saline water which contribute to complex refractive index of the medium and makes attenuation higher as well. As the ions absorb laser photons, energy is lost and scattering happens through the non-uniform distribution of suspended particles and changes in the refractive index brought on by salinity gradients [10,11]., Many studies have shown that red-light laser have a much larger attenuation coefficient in saline water than in freshwater. These results highlight the importance of accounting for salinity gradients in UWOC systems design, especially in regions with a range of aquatic ecosystems from estuaries to oceans [12,13]. In addition to the salinity affect, the temperature effect is another important factor has to consider based on UWOC. Temperature fluctuations can also alter the solubility and mobility of ions in water, which however in turn influences the optical properties of the medium [14,15]. Therefore the salinity and/or temperature are essential to accurately model and predict underwater red-light laser propagation. Recent progress in semiconductor laser technology has equipped the researchers with tools to minimize the detrimental impact of salinity on the UWOC systems. Various techniques like wavelength adjustment, beam transformation, and adaptive modulation protocols can increase the robustness of red-light laser signals against scattering and absorption [16,17].

2. METHOD Theoretical and Background.

The medium and the geometric arrangement of the light specifically, whether it is a collimated or diffused beam are the two main determinants of the apparent optical properties (AOPs)[18]. Among the various advantages of the seeming qualities are the following. First, the optical beam's directional quality is determined by its apparent qualities. Secondly, they are used to measure the ambient light levels for communication in the vicinity of the water's surface [19]. Third, AOPs play a critical role in radiant energy penetration into the ocean's depths [20]. The most prevalent apparent characteristics are reflectance, irradiance, and brightness. Regular and consistent illumination sources can create the apparent characteristic. Because it varies with the time of day and the weather, the down welling irradiance from the Sun is therefore not regarded as a definite property [21]. One optical characteristic that depends on the geometry of the light field is the diffuse attenuation coefficient [5, 8, 22]. In those cases, either a normalized or ratios of properties that are equally affected by the environment are considered. Ocean waters vary due to changes in water types both vertically and regionally. The vertical difference depends on the amount of light received from the sun in addition to decreased background radiation, and the geographical variance varies from coastal locations to ocean clarity [17, 23]. Even though there are many different kinds of water, they can be divided into coastal and oceanic regions based on the amount of sunlight that reaches the bottom of the well [23]. There are four primary categories of water in the oceanic group. Pure seawater is frequently given particular attention in the literature because of its low scattering, which causes the beam to go in a virtually straight line, yet absorption is still more common there, resulting in a greater loss of information than scattering. Because of the high concentration of dissolved particles in clear ocean water, scattering is the main factor and has a significant impact on overall attenuation. The primary limiting factor in coastal ocean water is phytoplankton-induced absorption [24, 25, 26, 27, and 28].

2.1. Read Laser Transmission in the Aquatic Medium.

The two main hindering phenomena that occur when light travels through water are absorption and scattering. The absorption coefficient $A_{(\lambda)}$ and the scattering coefficient $S_{(\lambda)}$ are commonly used to assess the energy loss resulting from absorption and scattering, respectively. The attenuation coefficient, as described by [17, 18], can also be used:

$\alpha(\lambda) = A_{(\lambda)} + S_{(\lambda)}$ ……………………………………(1)

There are many type of substances are responsible for modifications of seawater properties. These substances of seawater include phytoplankton, non-chlorophyllous particles of biologic, dissolved organic matter and/or salt concentration. However, The water type and wavelength λ determine the values of $A_{(\lambda)}$ and $S_{(\lambda)}$. To keep things simple, the values of the chlorophyll content C are employed to describe the various types of water [17, 23]. Consequently, it is possible to represent the values of $A_{(\lambda)}$ and $S_{(\lambda)}$ as a function of wavelength and concentration [29,30, and 31]:

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

$S_{(\lambda)} = 0.30 \frac{550}{\lambda} C^{0.65}$ ……………………………………(3)

Here the $\mathbf{a_w}$ is stands for clean water's absorption coefficient and $\mathbf{a_c}$ is the water's phytoplankton pigments' normalized spectrum absorption coefficient [28,30]. The values of $\mathbf{a_w}$ and $\mathbf{a_c}$ have been given based on *L. Prieur* literature [22].

Propagation of laser light in saline water is obeys Beer's Law which describes the exponential decay of light intensity due to absorbing and scattering processing of the medium [6, 17].Therefore, received optical power $P_r(\lambda)$ at laser wavelength λ and range R for the UWOC can be obtained based on equation 4. Here the $P_t(\lambda)$ is the transmittance optical power from transmitter [23].

$P_r(\lambda) = P_t(\lambda)\, e^{-\alpha(\lambda)R}$ ……………………………………….(4)

The attenuation coefficient can be calculated from the measured received optical power in addition to the theoretical calculation [32].

$\alpha(\lambda) = \frac{I}{R} \ln \frac{P_r(\lambda)}{P_t(\lambda)}$ ………………………………………………(5)

The signal quality of the best performance in UWOC refers to the ability to distinguish received signals as legal information and ignore any other signal. The signal-to-noise ratio (SNR) of UWOC is the proportion of signal power to noise power [24]. Based on equation 6, the P_n is the average noise power, and P_s is the average signal power.

$SNR = 10 \log \frac{P_s}{P_n}$ ……………………………………………………….(6)

In addition to the attenuation factor, UWOC effected directly by refractive index (n) change as a result of temperature and salinity variations. For Analytical data of n, Cauchy formula with temperature-dependent coefficients have been presented in equation 7 [33].

$n(\lambda, t) = A(t) + \frac{B(t)}{\lambda^2} + \frac{C(t)}{\lambda^4} + \frac{D(t)}{\lambda^6}$ ……………………………………..(7)

Based on this equation, the Cauchy coefficients *A (t), B (t), C (t), and D (t)* as a function of temperature (°C) have been roughly represented by three-degree polynomial equations (8-11) [33].

$A(t) = 1.3208 - 1.2325\, x10^{-5} t - 1.8674\, x10^{-6} t^2 + 5.0233\, x10^{-9} t^3$……………….(8)

$B(t) = 5208.2413 - 0.5179t - 2.284\, x10^{-2} t^2 + 6.9608\, x10^{-5} t^3$ ……………………………(9)

$C(t) = -2.5551x10^8 - 18341.336\, t - 917.2319\, t^2 + 2.7729\, t^3$ ……………………… (10)

$D(t) = 9.3495 + 1.7855\, x10^{-3} t + 3.6733x10^{-5}\, t^2 - 1.2932\, x10^{-7} t^3$……………………(11)

2.2. Experimental setup of the UWOC system.

The purpose of the experiment was to examine how optical signals behaved in relation to received power for 650 nm red laser with pulse width modulation (PWM). The received power was examined based on different salt concentrations levels in water channel as (UWOC medium). Typically, the underwater channel includes a water tank, a transmitter, and receiver. A rectangular glass tank with dimension (0.5 m x 0.25m x 0.25m) was employed as water channel. The glass water tank was covered with a black cover to avoid the background of surrounding photon effect such as scattering and reflections within the tank. Laser diode of wavelength 650 nm with output power of 5 mW and was used as transmitter. In addition to the Laser diode, the transmitter of the UWOC consists of Personal Computer (PC) used to write and send texts to the Microcontroller type (Arduino Uno). Based on the Microcontroller, the received texts from (PC) the laser signal can be modulated with a different pulse width relying on used program (uploaded code). The UWOC receiver has a photoresistor or light-dependent resistor (LDR), Figure 1.

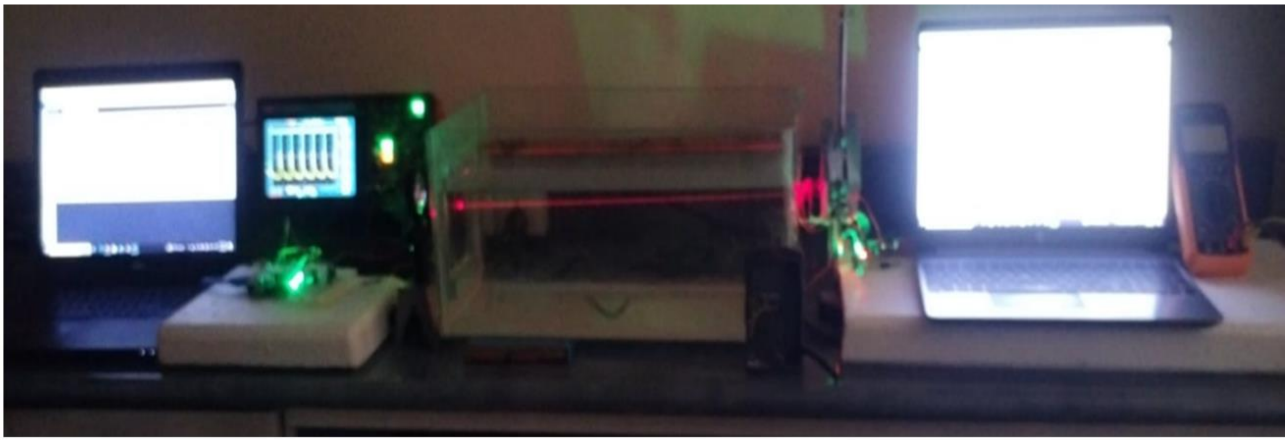

Figure 1. Experimental setup of underwater optical communication system demonstrations in the laboratory environment.

It used to detect and convert the optical signal to an electrical signal (demodulate). After that, the electrical signal can be received and analysis by PC as received message. The optical signal transmitted through the water channel was received by LDR in the receiver while the output power was observed and measured by optical power meter. The intensity of the laser power was measured in different salinity level with varying distance of the transmitting link. To receive the laser power in different saline water (salinity channel), water with different salt concentrations of (0 - 60) g/L was used as channel. Then, for each channel, received power at different channel length was observed. Figure 1 shows the experimental setup of UWOC of this work using pulse width modulation (PWM) for diode laser. In this scenario, point-to-point Line-of-Sight (LOS) configuration between transmitter and receiver was used with zero slope angles at UOWC. To measure the refractive index of water's channel, optical technique was employed based different water channel including temperature and salinity (tap water and water with 35g/L NaCl) [34,35].

3. Results and Discussion

Figure (2a) shows the analytical values of absorption and scattering coefficients at different wavelengths. It is found that absorption and scattering coefficients depending on the type of marine environment and used wavelength. At a specific wavelength, the coefficients of absorption denoted by (A) black curves and scattering denoted by (S) blue curves for Pure-Sea were lower compared to other environments such as Clean- Ocean and/or Costal-Ocean due to lower concentration of phytoplankton, nonchlorophyllous particles of biologic or terrestrial origin, and dissolved organic matter in the water [22, 28].The values of absorption and scattering coefficients also increased with increasing wavelength. At a wavelength of 650 nm, the values of coefficients of Pure-Sea were 0.6504m^{-1} for absorption and 0.0095m^{-1} for scattering, while the values of coefficients for Costal-Ocean were significantly higher, reaching 0.29151m^{-1} scattering and 0.37469 m^{-1} absorption. As can be seen, the water type has been shown no significant influence on the absorption coefficient compared to scattering coefficient. These results indicate the influence of wavelength and marine environment type on absorption and scattering properties, come from environmental diversity in the properties of marine materials across different wavelengths [16, 17]. However, the scattering process at specific water type decreases with increasing the wavelength. Absorption is influenced by the levels of humic acid, fulvic acid, and chlorophyll [22, 28]. The spectra's scattering is affected by biological elements like of dissolved phytoplankton and nonchlorophyllous particles [17, 19, 23]. Figure (2b) showing that the attenuation coefficients are depending on the marine environment (water type) and wavelength. At 650 nm wavelength, the attenuation values in the pure-sea environment were lower than in the other environments, where the value was 0.3601 m^{-1}, while it doubled to reaches 0.6662 m^{-1} for the coastal-ocean. It was noted that, with increasing wavelength a significant increase in the attenuation coefficient values for all marine environments, where the values reached to 0.6592m^{-1} in the pure-sea at 700 nm wavelength, while in the coastal-ocean it reached 0.9356m^{-1}.

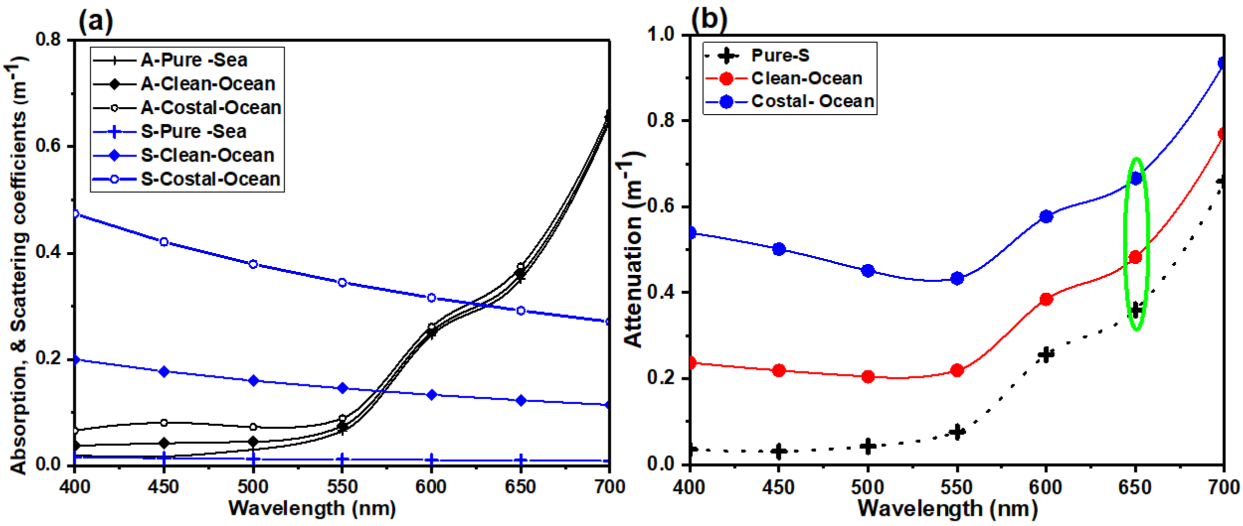

Figure 2. Analytical values of Absorption (A), and Scattering (S) coefficients (a). Analytical values of Attenuation coefficient (b). All the results estimated for pure see water, clean and costal ocean.

These results indicate the effect of wavelength and marine environment type on the attenuation coefficients, where the attenuation coefficients increase with increasing wavelength in all environments. Based on the analytical values of the attenuation coefficient at 650nm, the theoretical values of received power at different environmental conditions were plotted in the Figure (3a) as a function of underwater range. The results show that the received power decreases with increasing underwater distance in all marine environments. At 10 cm, the highest received power value was in pure-sea, reaching 4.2621mW, while it was lowest in coastal-ocean, reaching 3.3272mW. As the distance increased to 100 cm, the received power decreased in all environments reaching to 0.6422 mW in pure-sea and to 0.2152 mW in coastal-ocean. These results indicate the influence of the marine environment and underwater range on the received power. Figure 3b shows the results of salinity effect onto the received power. The results indicate that the received power decreases with increasing the salinity concentration and underwater distance. At a distance of 10 cm, the received powers was 4.531 mW for tap water, while, they were 4.017 mW, 3.668 mW, 3.456 mW, 3.272 mW, 3.173 mW, 3.053 mW, 2.9333 mW, 2.786 mW, 2.576 mW, and 2.352 mW for water salinity concentration of 5 g/L, 10g/L, 15g/L, 20g/L, 25g/L, 30g/L, 35,g/L, 40 g/L, 50 g/L and 60 g/L respectively. As the distance increased to 100 cm, the received power decreased at all salinity levels, reaching 0.6346 mW in tap water, while in water with a salinity concentration of 60 g/L it was 0.00137 mW.

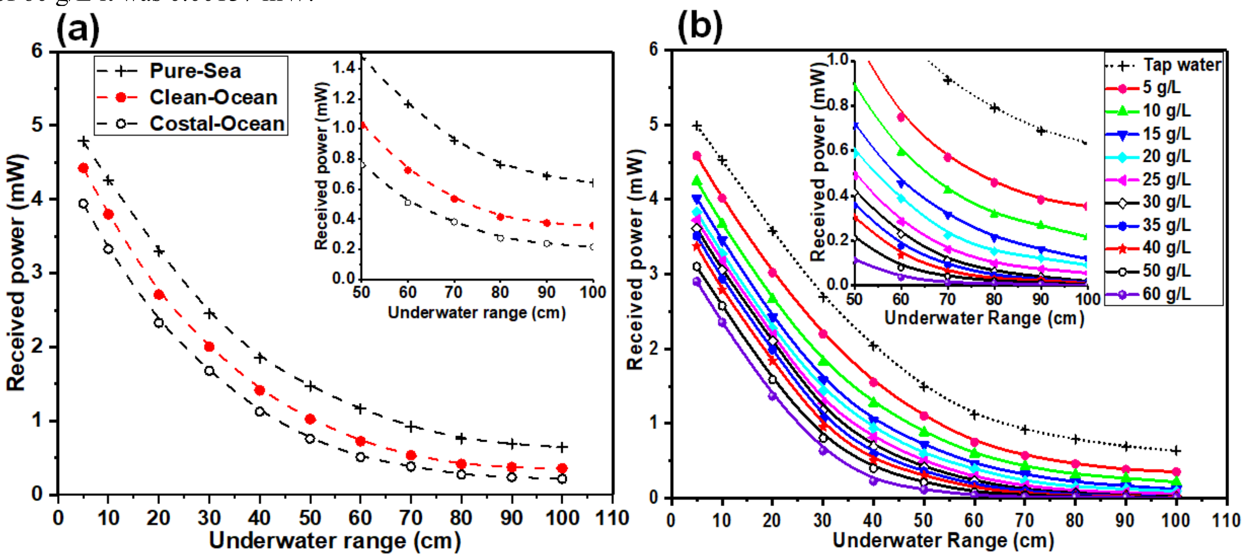

Figure 3. Analytical values of received optical power estimated for pure see water, clean and costal ocean (a). Experimental results of received power based different salt concentrations (b).for different length of water channel.

These results indicate that increasing water salinity leads to a further decrease in the received power at given distance due to the negative effect of salinity on underwater signal transmission [36]. However, the received power curves for analytical and experimental are almost same behavior for all water types (salty water and/or tap water). Signal-to-Noise Ratio (SNR) has shown in Figure (4a) as a function of underwater range and different salt concentration.

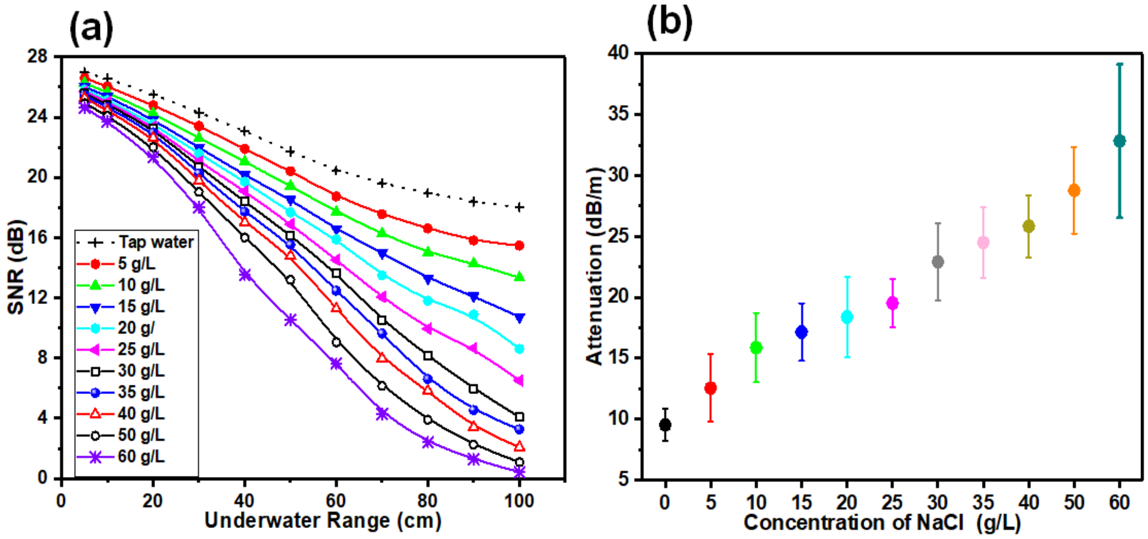

Figure 4. SNR based different salinity concentration of water channel (a). Division of Attenuation coefficient based different salinity concentration measured at 100 cm length of water channel (a).

Based on equation 1, it was noticed that the SNR for tap water decreased from 26.981 dB in the transmitter to 18.025 dB in the receiver at maximum transmission underwater range of 1 meter due to the attenuation that was dominate by absorption process of the light by fresh water. In the other hand, the SNR degrade in presence of water salinity. It was found that, at 25g/L slat concentration the SNR for drops from 25.711 dB in the transmitter to 6.512 dB in the receiver for 1 meter underwater range. Increasing water salinity led reduced the SNR further to be 0.4279 dB in the receiver for 1 meter underwater range at 60g/L slat concentration. However, dropping the SNR at the receiver in the present of salt concentration indicated a strong effect of salinity on optical signal transmission due to the attenuation that dominating by scattering process of the light by saline solutions [37]. As can be seen in the Figure (4b), the deviation of attenuation was observed experimentally based on received optical power equation 5. For 1 meter underwater range, the mean value of attenuation was 9.5157dB/m for tap water, and then it increases to reach 31.8157dB/m for 60g/L slat concentration. This finding is attributed to the scattering process of the light by saline solutions which lead to poor received signal at the receiver and overall poor efficiency of UWOC system [36]. The error bars indicate variability in measurement of received signal of the power based on pulse width modulation which could lead to variation in measured values of the attenuation. In addition to impact of the salinity and/or impurities onto the UWOC, the poor received signal may be attributed to other factors such as the refractive index and/or water deep (temperature) [38],

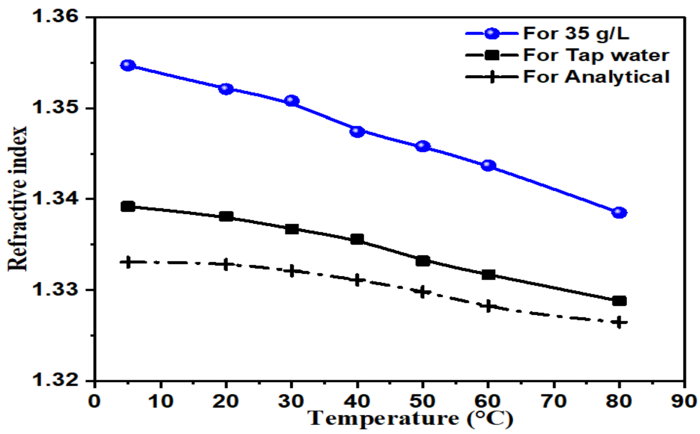

Figure 5. Experimental and Analytical refraction index based on 650 nm wavelength and different water channels and temperatures.

The experimental and analytical results of the refractive index have been plotted in Figure 5. based on 650nm laser wavelength and different water channels. As can be seen, the analytical results of refractive index based on 650nm were affected by temperatures leading to reduce it from 1.3398 at 5 °C to 1.3288 at 80°C. For the approximately same curve behavior, the experimental results of refractive index showed significant effect of both temperature and salinity. In tap water, the refractive index was highest at low temperature of 5°C, while it decreased slightly when the temperature increased to 80°C due to the low density of water. As can be seen, the saline water demonstrates a higher refractive index due to the increased density of water caused by dissolved salts reach to 1.3547 at 5°C and 1.3385 at 80°C. However the analytical results of refractive index are closely matched to the experimental values, with some minor deviations. Increased salinity leads to a higher refractive index due to the light refraction and finally attenuation which is potentially impact the efficiency of UWOC system [37,38]. Therefore, these factors must be carefully considered when design optical wireless communication systems for underwater environments to ensure reliable signal transmission. However, as the temperature increases in the seawater, the salinity of water decreases leading to changes the temperature and finally the seawater density [38]. Furthermore, the impact of salinity onto efficiency of UWOC system was further confirmed with oscilloscope record of wavefrom as illustrated in Figure 6. As shown in the Figure, series of oscilloscope screenshots illustrating how varying concentrations of salt affected onto the transmission of optical signals through the water channel. Each waveform is analyzed individually based on salinity levels that impacts onto shape and quality of the transmission signal. In tap Water, the waveform appears clear and well-defined, indicating strong and efficient light transmission. The peaks are sharp and stable, suggesting minimal attenuation and distortion. The minor variations in amplitude could be attributed to natural system noise. At very low salt concentration (5-10)g/L, the waveform starts to lose some clarity with noticeable attenuation appear due to increased light absorption and scattering. However, signal is still strong and reliable, with only a slight reduction in intensity. For mid salt concentration (15-25)g/L, the waveform becomes less defined with amplitude drop indicating higher absorption and scattering of light. This situation leads to irregular edges of the waveform and finally decline in transmission quality. Further increasing the salt concentration to 60g/L, the signal was almost lost with the waveform appearing extremely weak, breakdown, and unclear. This result was due to scattering process which becomes more dominated onto transmitted signal at the maximum transmission link.

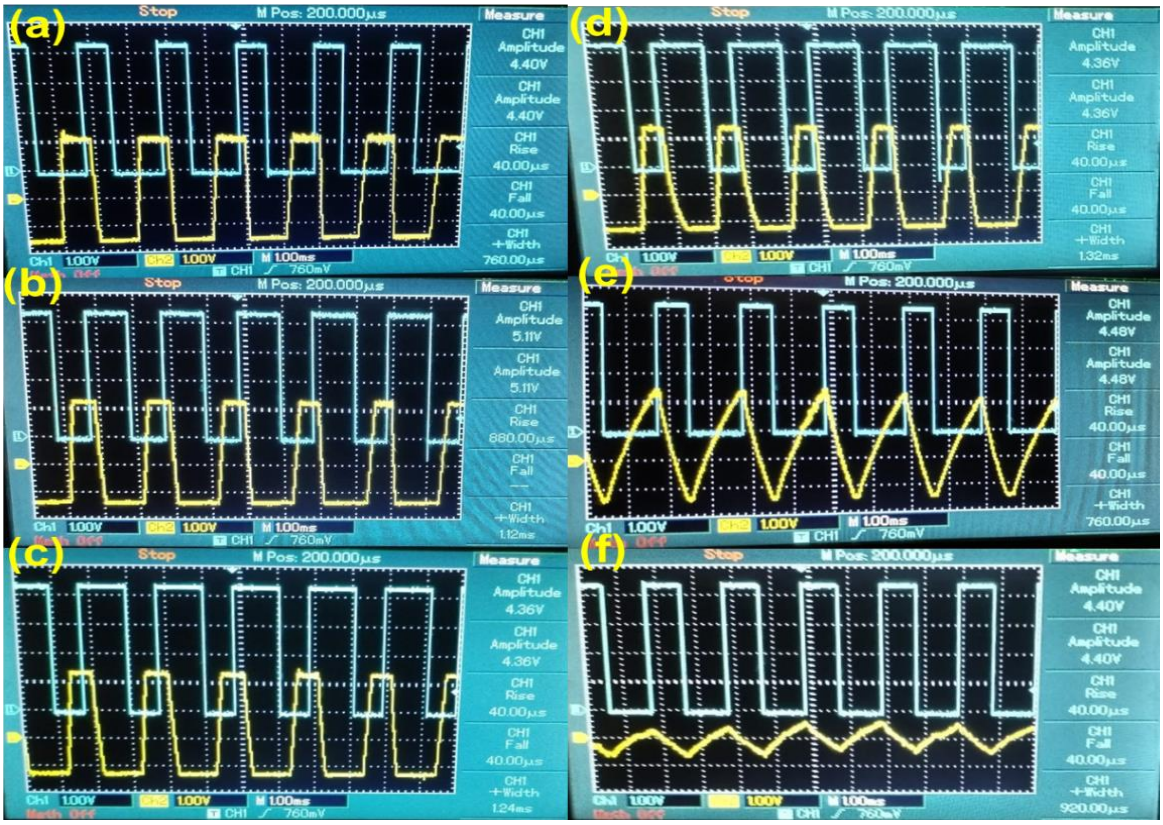

Figure 6. Waveform of Red laser (650) nm at maximum transmission link along water channel for tap water (a), 5g/L of NaCl (b), 10g/L of NaCl (c), 15g/L of NaCl (d), 25g/L of NaCl (e) and 60g/L of NaCl (f).

4. CONCLUSION

The UWOC system has been designed based on 650 nm red laser of 5 mW as transmitter. Different types of water channels namely tap water and saline water with different concentration has been used to examine the performance of UWOC laboratory system. Analytical values of absorption and scattering coefficients based on 650 nm red lasers show no significant influence on the absorption coefficient compared to scattering coefficient. This finding indicated that the scattering process at specific water type decreases with increasing the wavelength. This investigation is important to select 650 nm red lasers as best visible widow of efficient UWOC system especially for saline water. It was found that the amount of losses in power at receiver at maximum underwater link decrease with increasing salt concentration due to the negative effect of salinity on underwater signal transmission. The result show that, at distance of 10 cm, the received powers were 4.531 mW for tap water, then it becomes 2.352 mW for saline water of concentration 60 g/L. However, the received power curves for theoretical and experimental are almost same behavior for all water types. It was found that increase the water salinity led to further reduced the SNR from 18.025 dB of tap water to reach 0.4279 dB at the higher slat concentration of 60g/L in the receiver for 1 meter. However, dropping the SNR at the receiver in the saline water was due to the optical signal transmission loss that dominating by scattering process of the light by saline solutions. It was noted the performance of UWOC could be effected by others parameter such as the refractive index which is individually as function to the different parameter like wavelength, temperatures and optical density of the medium.

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