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A review on how to investigate the effects of salinity on underwater fiber optics

Mohammad Mehdi Esmailian*

Master in Physics, School of Fundamental Sciences, Payame Noor University, Bushehr, Iran

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Abstract

This study tries to review the investigating procedure of salinity effects on the performance of underwater fiber optic systems, crucial for marine communication and sensing applications. It will be tried to assess how varying salinity levels influence light transmission, signal attenuation, and overall system reliability. The results indicate that increased salinity correlates with higher attenuation rates due to changes in refractive index and scattering effects. Additionally, specific wavelengths are more susceptible to these changes, impacting data integrity over long distances. The study suggests that optimizing fiber optic design and materials for high-salinity environments can enhance performance and longevity, providing valuable insights for future underwater communication technologies. Fiber optics are widely used in various applications, including telecommunications, medical devices, and industrial sensors. However, their performance can be significantly affected by environmental factors, particularly in saline environments such as coastal areas or marine applications. This case study reviews the resistance of different fiber optic materials to degradation and corrosion when exposed to saline conditions. The analysis reveals that as the salt concentration in the water increases, the performance of underwater optical fiber is declined.

Keywords: Optical fiber; Underwater technology; Salinity; Correlation; Submarine fiber.

1. Introduction

Fiber optics involves the transmission of data as light pulses through thin strands of glass or plastic fibers. Fiber optics technology is used in different fields; submarine

* Corresponding Author's Email: m.mesmailian@pnubu.ac.ir

communication, oceanographic research, underwater robotics and autonomous vehicles. This technology has some advantages such as: High bandwidth, low signal attenuation, immunity to electromagnetic interference, and lightweight (Schirripa Spagnolo *et al*., 2020). Recent Advances can be represented as follow:

- Development of robust materials resistant to harsh underwater conditions.
- Innovations in multiplexing techniques to enhance data transmission rates.
- Integration with wireless technologies for hybrid systems.

Moreover, there are different factors that effect on the underwater fiber optics:

- Environmental Factors: Saltwater corrosion, biofouling, and temperature variations.
- Installation Difficulties: Complex logistics for laying cables on the seabed.
- Signal Loss: Scattering and absorption in water can affect signal quality.

Active optical systems use lasers for long-distance communication and passive optical systems: Utilize ambient light for short-range applications. Furthermore, fiber optics using different technologies; Distributed Acoustic Sensing (DAS), Distributed Temperature Sensing (DTS), can have monitoring on the environment (temperature, pressure, salinity), and Structural health of underwater infrastructure (bridges, pipelines). It also monitors the marine life tracking (He and Liu, 2021).

Integrating sensors within underwater installations to monitor environmental conditions (including salinity) allows for proactive maintenance strategies. The salinity is a cause of signal disappearing, and acoustic waves speed in enhanced by 1.4m/s while rising salinity 1 practical salinity unit (PSU). According to delivery signals over long distances under consideration of plane wave model or spherical wave model, emerging technology is widely known as UWSNs, which is alternative and a complimentary communication media solution, especially for military and naval tactical, operational applications (Mei *et al*., 2020).

2. Salinity Effects

Salinity is defined as the concentration of dissolved salts. 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 (Kumar *et al*., 2020). The typical ocean salinity is around 35 ppt (gm/L) as (Boyd, 2019). Varying salinity levels in seawater affect its refractive index, which consecutively influences signal transmission, mainly for optical and acoustic signals by altering the speed and direction of the signals. Higher salinity can lead to greater refraction, potentially causing signal distortion or loss of clarity. In underwater communication systems, these variations must be accounted for to ensure effective transmission (Kumar *et al*., 2020).

The relationship between salinity, refractive index, and attenuation in water is a complex interplay of physical properties. Here's a breakdown of why increasing salinity can lead to higher attenuation rates, particularly in the context of light propagation in seawater. Higher salinity due to the higher concentration of dissolved salts, leading to reduced clarity and range of optical signals, while acoustic signals may experience changes in speed and direction, affecting communication and navigation systems in marine environments. In fact, salinity refers to the concentration of salts in water, primarily sodium chloride (NaCl), but also includes other dissolved ions such as magnesium, calcium, and sulfate. Higher salinity alters its optical properties, which can influence light transmission in several ways. In fact, fiber optic cables transmit data as light signals through a core made of glass or plastic, surrounded by cladding that reflects light back into the core. The efficiency of this transmission depends on several factors, including the refractive index of the materials involved and external environmental conditions (Kumar and Vats, 2021):

1. Refractive Index Changes

   Increased salinity raises the refractive index of water, which can affect the critical angle for total internal reflection in fiber optics, due to the presence of dissolved salts. This may lead to changes in signal attenuation and potential loss of signal quality and also light propagation in fiber optics by altering the critical angle for total internal reflection.

   - Refractive Index Increase: As salinity increases, the refractive index of seawater also increases. This is because dissolved salts (like sodium chloride) increase the density and change the optical properties of water.
   - Light Bending: A higher refractive index means that light bends more as it enters the water from air. This bending can lead to increased scattering at interfaces and within the medium itself.

2. Scattering coefficients

   Saline water can increase light scattering because of dissolved salts and particulates, potentially reducing the effective range and clarity of signals transmitted through fiber optics (Gawdi, 2006).

   - Increased Particle Concentration: Higher salinity often correlates with an increase in dissolved and suspended particles (like phytoplankton, organic matter, or inorganic sediments). These particles scatter light more effectively.
   - Mie Scattering: The presence of these particles can lead to Mie scattering, which occurs when the size of the scattering particles is comparable to the wavelength of light. This type of scattering is particularly significant in turbid waters.

3. Absorption coefficients

   Increasing salinity of water can rise the absorption coefficients of light due to disbanded particulars, possibly decreasing the actual range of signals transmitted through fiber optics.

- Chemical Composition: Salts and other dissolved substances can absorb specific wavelengths of light more effectively than pure water. This absorption contributes to overall attenuation.
- Wavelength Dependence: Different ions have different absorption characteristics at various wavelengths, which can further complicate how light propagates through saline water.

4. Corrosion and Material Integrity
   High salinity environments can accelerate corrosion of protective coatings or materials used in underwater cables, potentially leading to physical damage or degradation over time.
5. Temperature Effects
   Salinity often correlates with temperature variations, which also affect the refractive index and performance of optical fibers.
6. Density and Buoyancy
   Saline water is denser than freshwater, which can influence cable buoyancy and stability in marine environments.

Overall, while fiber optic cables are designed for underwater use, High-salinity conditions can still pose challenges that need to be considered during installation and maintenance. These factors collectively contribute to higher attenuation rates in optical fibers exposed to saline environments.

3. Material and methods

The performance of various fiber optic materials in saline environments should be evaluated. Moreover, the mechanisms of degradation and corrosion specific to each material are identified and suitable materials for use in saline conditions are recommended. Using advanced materials that resist corrosion and biofouling is crucial for enhancing durability. Different fiber optics' materials can be studied (Méndez and Morse, 2011):

- Glass Fiber Optics (Silica-based)
- Plastic Optical Fiber (POF)
- Polymer Coated Fiber Optics
- Specialty Fibers (e.g., Fluoride Glass Fibers)

3.1. Methodology

To investigate the effects of varying salinity levels on light transmission and attenuation in aquatic systems, and to evaluate the reliability of measurement systems under these conditions (Qian *et al*., 2018).

1) Sample Preparation:

Samples of each type of fiber optic should be prepared with standard dimensions and coatings where applicable.

2) Exposure Conditions:

The samples would be submerged in a saline solution (3.5% NaCl) at room temperature for varying durations (1 month, 3 months, 6 months).

3) Testing Parameters:

- Optical Transmission Loss: Measured using an optical time-domain reflectometer (OTDR).
- Mechanical Strength: Evaluated through tensile testing.
- Surface Analysis: Conducted using scanning electron microscopy (SEM) to observe surface morphology changes.
- Chemical Analysis: X-ray photoelectron spectroscopy (XPS) was used to analyze any chemical changes on the surface

4. Results and Discussion

Through representing some experiments and knowledge management, the effect of salinity changes on the underwater fiber optics and a light resource can be analyzed and investigated by a defined procedure.

Experiment title	Objective	Materials	Method and procedure	Data Analysis
Baseline Light Transmission Measurement	Establish baseline light transmission in freshwater	Light source (e.g., LED or halogen lamp) -Light sensor (photodiode or photometer) -Clear water samples -Measuring cylinder or cuvette -Data recording equipment	1. Fill a measuring cylinder with distilled water. 2. Position the light source at one end and the light sensor at the other. 3. Measure and record the intensity of light transmitted through the water. 4. Repeat measurements at different distances (e.g., 10 cm, 20 cm, 30 cm) to establish a baseline for attenuation in freshwater.	1. Use statistical software to analyze data trends across different salinities and conditions. 2. Create graphs showing relationships between salinity levels and both light transmission/attenuation coefficients. 3. Assess reliability by calculating standard deviations and confidence intervals for repeated measures

Varying Salinity Levels	Assess how increasing salinity affects light transmission and attenuation	Salt (sodium chloride) - Freshwater	1. Prepare saline solutions with varying salinity levels (e.g., 0 ppt, 5 ppt, 10 ppt, 15 ppt, 20 ppt). 2. For each salinity level: - Fill a measuring cylinder with the saline solution. - Measure and record light intensity transmitted through each solution at various distances. 3. Calculate attenuation coefficients for each salinity level using Beer-Lambert Law.	
Long-term Stability Testing	Evaluate system reliability over time under different salinities	- Timer or data logger for continuous monitoring	1. Select two or three representative salinity levels based on results from Experiment 2 (e.g., low, medium, high). 2. Set up continuous monitoring of light transmission over an extended period (e.g., several hours to days). 3. Record any fluctuations in readings due to environmental factors (temperature changes, evaporation). 4. Analyze data for consistency and reliability across different conditions.	
Impact of temperature on light transmission	Investigate how temperature interacts with salinity to affect light transmission	- Water bath or temperature-controlled environment - Thermometer	1. Prepare saline solutions at selected salinities from previous experiments. 2. Adjust temperature settings (e.g., room temperature vs elevated temperatures).	

			3. Measure light transmission as described in previous experiments while maintaining constant temperature conditions. 4. Analyze how temperature variations impact results across different salinities.	

4.1. Salinity effects on underwater fiber optics

The results indicate that glass fiber optics exhibit superior resistance to degradation and corrosion compared to plastic optical fibers and polymer-coated options when exposed to saline environments. The inert nature of silica contributes significantly to its durability under harsh conditions. Plastic optical fibers demonstrated considerable vulnerability due to their hydrophilic nature, leading to increased transmission losses and mechanical weakening over time. Polymer-coated fibers showed moderate performance.

The effects of salinity on underwater fiber optics encompass a range of physical phenomena affecting signal transmission, material integrity, and overall system reliability.

1) Glass Fiber Optics
   - Optical Transmission Loss: Minimal increase in loss over 6 months; average increase was about 0.05 dB/km.
   - Mechanical Strength: Retained over 90% of initial tensile strength after exposure.
   - Surface Analysis: No significant corrosion or degradation observed; silica showed high resistance due to its inert nature.
2) Plastic Optical Fiber (POF)
   - Optical Transmission Loss: Significant increase in loss after 3 months; average increase was about 0.5 dB/km due to plastic swelling and water absorption.
   - Mechanical Strength: Reduced by approximately 30% after exposure; plastic showed signs of softening and brittleness.
   - Surface Analysis: SEM revealed surface pitting and micro-cracking indicative of chemical degradation.
3) Polymer Coated Fiber Optics
   - Optical Transmission Loss: Moderate increase in loss; average increase was about 0.2 dB/km after 6 months due to coating breakdown.

- Mechanical Strength: Retained about 80% strength; however, some fibers exhibited delamination at the coating interface.
- Surface Analysis: XPS indicated leaching of polymer components into the saline solution.

4) Specialty Fibers (Fluoride Glass)

- Optical Transmission Loss: Increased loss similar to glass fibers but slightly higher at around 0.1 dB/km due to ion exchange processes with salt ions.
- Mechanical Strength: Maintained over 85% strength; however, some fibers showed susceptibility to stress corrosion cracking under prolonged exposure.
- Surface Analysis: SEM showed minimal surface alteration but indicated potential for ion exchange leading to localized weakening.

4.2. Effects of salinity on Signal Transmission

- Attenuation: The increased refractive index from higher salinity can lead to changes in signal attenuation rates. While fiber optics are designed to minimize loss, variations in external conditions may introduce additional scattering or absorption losses.
- Dispersion: Changes in temperature and salinity can affect dispersion characteristics within the fiber optic cable itself. This could lead to signal distortion over long distances.

4.3. Corrosion and Material Integrity

- Cable Materials: Most underwater fiber optic cables are designed with protective coatings to prevent corrosion from seawater; however, high salinity levels can accelerate corrosion processes in metallic components (e.g., connectors or armoring).
- Microbial Growth: Saline environments may promote biofouling—growth of microorganisms on cable surfaces—which can further impact performance by introducing additional resistance or physical damage.

4.4. Temperature Interactions

Salinity often correlates with temperature variations in marine environments. Temperature changes can exacerbate the salinity effects on optical fibers:

- Higher temperatures generally increase attenuation rates.
- Thermal expansion may affect mechanical integrity if materials respond differently to temperature changes.

4.5. System Reliability Assessment

To assess overall system reliability, considering following procedures is a key task:

- A reliability analysis chart that shows how consistent your measurements are across trials at each salinity level.
- A risk assessment matrix that evaluates potential factors affecting reliability, such as equipment calibration errors or environmental changes during sampling.

Conclusions

Fiber optics technology is pivotal for advancing underwater communication and sensing capabilities, offering high-speed data transfer and precise environmental monitoring despite inherent challenges. Continued innovation will further enhance its applications in marine environments. In summary, increasing salinity leads to a higher refractive index which affects how light propagates through water by increasing scattering due to suspended particles and enhancing absorption due to dissolved substances. Together, these factors contribute to a higher overall attenuation rate for light in saline environments compared to freshwater systems.

Implications for underwater communication systems, environmental monitoring, and potential improvements in fiber optic design for marine use.

- Increased use in smart ocean initiatives and marine IoT applications.
- Enhanced sensing capabilities through advanced fiber optic sensors.
- Expansion of global underwater fiber optic networks for improved connectivity.

To address these challenges posed by salinity, implementing protective coatings that provide barriers against saline intrusion can help maintain signal integrity over time. Furthermore, by following this experimental design and creating suitable diagrams, it can be effectively visualized how varying salinity levels influence light transmission and attenuation in water environments while also assessing system reliability through careful data collection and analysis methods.

Future research directions

Further research is needed to understand fully how varying levels of salinity interact with different types of optical fibers under diverse environmental conditions:

- Investigating new materials that could withstand extreme saline conditions without degradation.
- Developing models that predict performance based on real-time environmental data could enhance operational efficiency for underwater communication networks.

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