UPISC UNIVERSITY OF PITTSBURGH INFRASTRUCTURE SENSING COLLABORATION WORKSHOP

NATIONAL ENERGY TECHNOLOGY LABORATORY

# Distributed Fiber Optic Chemical Sensing for marine $CO_2$ Detection and Removal applications


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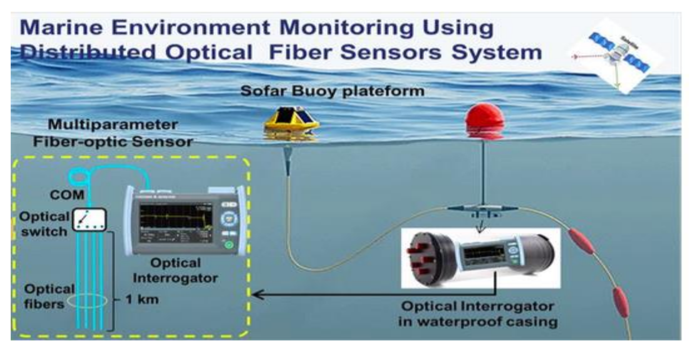
## Introduction

Accurate, low-concentration $CO_2$ detection is crucial for environmental monitoring, particularly in oceanographic studies. Exceptional absorption of anthropogenic-derived $CO_2$ emissions has decreased the pH of the surface oceans, known as ocean acidification (OA) which will significantly impact the marine environment.

**Fiber optic sensors** which are immune to EM interference offer more stable distributed chemical sensing with high sensitivity, resolution as well as fast responses in extreme harsh conditions.



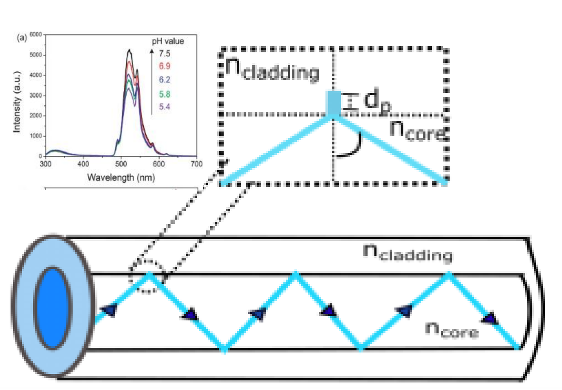

## Research Objectives

- **Hybrid Distributed fiber optic pH and $CO_2$ Sensing for Monitoring and Verification of Marine Carbon Dioxide Removal Applications**
  - Quantitative characterization of carbon-related oceanographic properties
  - Distributed Chemical (pH and $CO_2$) Sensing (DCS) using sensing layer integrated fibers
  - Selection and synthesis of polymer-based sensing layers and additives for pH and $CO_2$ sensing
  - Demonstration of distributed pH and $CO_2$ sensing in seawater application

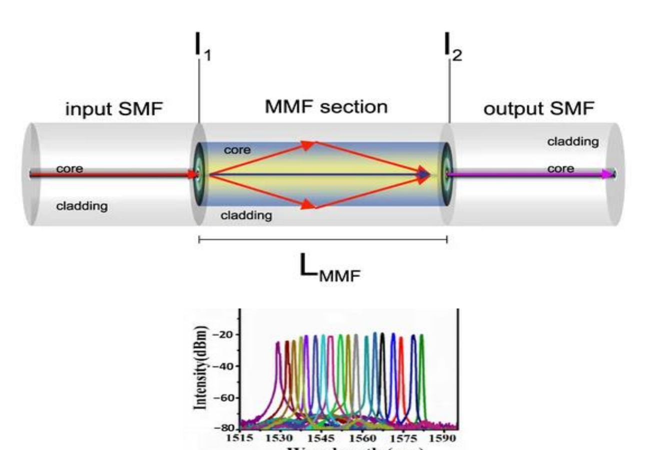
### Initial specifications for evanescent-wave-based distributed sensing

| | Distributed pH sensing | Distributed $CO_2$ sensing |
|---|---|---|
| Range | pH 5.00 - pH 9.00 (point) | 200 – 1500 ppm (point) |
| Resolution | 0.01 pH (point) | +/- 5 ppm (point) |
| Spatial range | ≥ 1Km | ≥ 1Km |
| Spatial resolution | ≤ 5m | ≤ 5m |

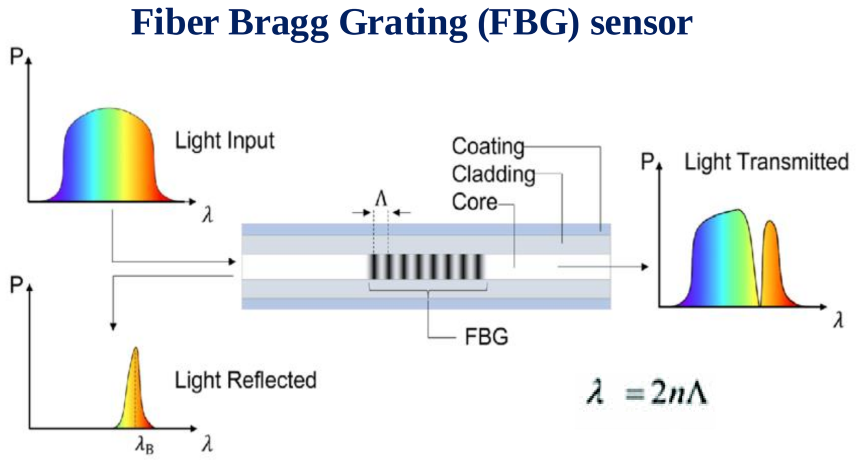
Evanescent wave absorption/ intensity based optic fiber sensor



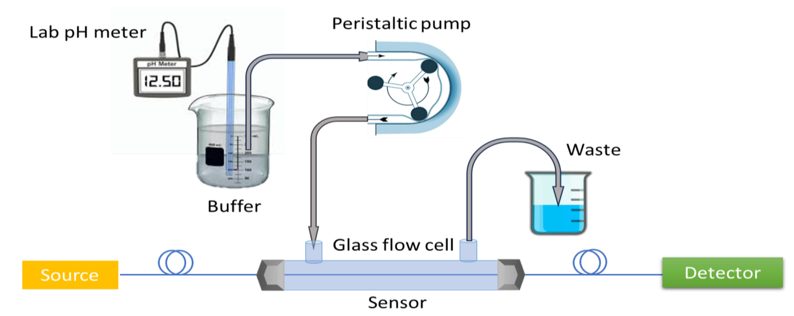
Interferometric/ wavelength based optic fiber sensor

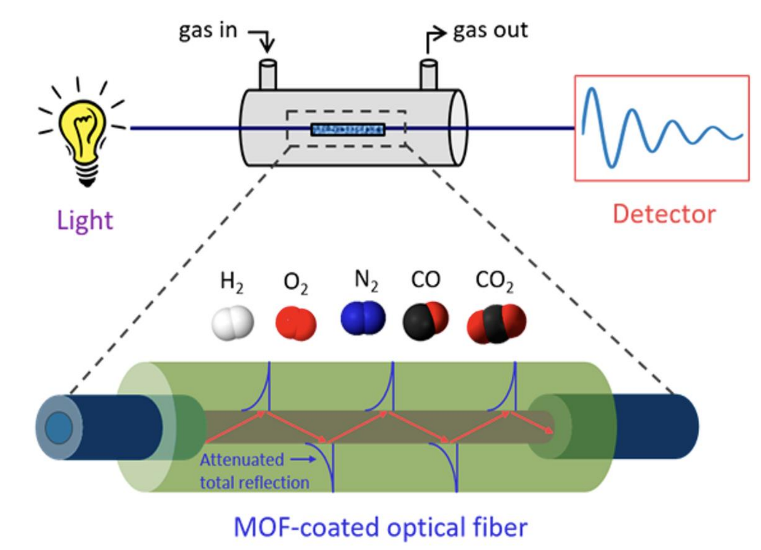


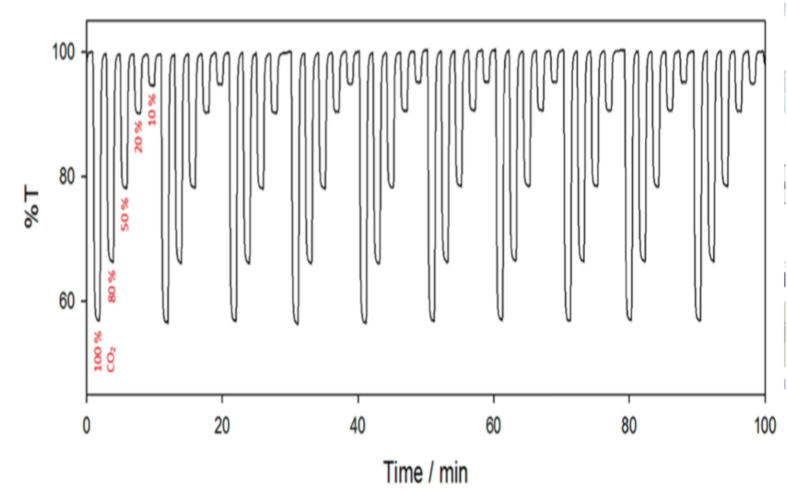

Fiber Bragg Grating (FBG) sensor




## Sensing test setups



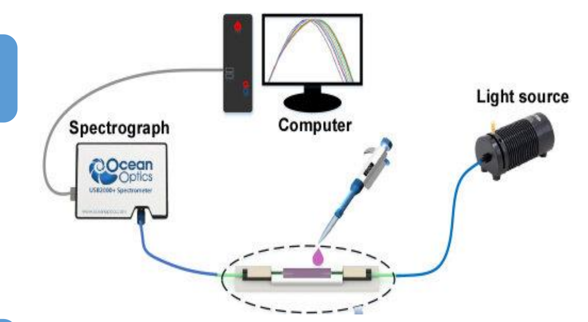




## Primary pH sensing mechanisms

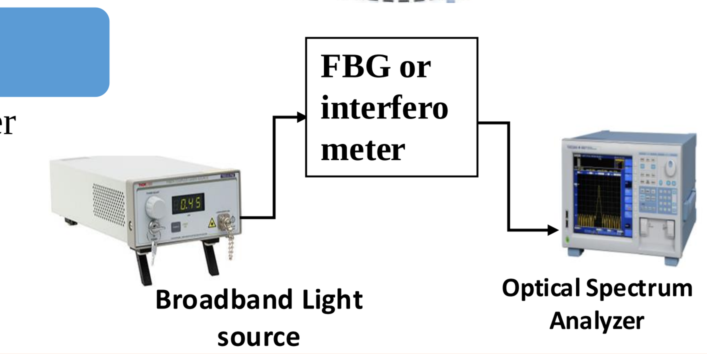
### Absorbance-based pH sensing

- Principle: Change in absorption or fluorescence properties of a pH sensitive indicator results in a change in the intensity of the light transmitted through the fiber
- Sensing element: pH sensitive indicator
- Measured parameter: Intensity of transmitted light




### Strain-based pH sensing

- Principle: Swelling or shrinking of pH sensitive material induces strain on the fiber causing change in refractive index and hence light propagation through the fiber
- Sensing element: pH sensitive hydrogel or polymer
- Measured parameter: Wavelength shift or intensity




## Sensing materials for pH sensing

| Sensing mechanism | pH sensing layer | Synthesis method | Compatibility with reel-to-reel coating | Advantages |
|---|---|---|---|---|
| Absorption | **TOES-DDS** sol-gel Indicator: meta-Cresol Purple | Entrapment of indicator dye in sol gel matrix | Could be (Dip coating) | Promote hydrophobicity, reduce dye leaching, reduce film cracking, fast response |
| Strain | Conducting polymer: **Polyaniline (PANI)** | Oxidative polymerization | May not be (In situ polymerization) | Excellent environmental stability in its different forms, resistance to solvent, Absorption coefficient in visible and NIR region |
| | **Smart Hydrogel**: polyacrylamide | Photopolymerization | Yes (Dip coating) | Excellent linearity over pH 5 – 9, stability, repeatability and fast response |

## Sensing materials for $CO_2$ sensing

| Material | Refractive Index | Hydrophobicity | $CO_2$ Detection Limit | Notable Properties |
|---|---|---|---|---|
| **PDMS** | ~1.41 | High | To Be Determined | Biocompatible, flexible |
| **ZIF-8** | ~1.4 | Moderate | TBD | High surface area, tunable porosity |

## Synthesis of $CO_2$ sensing layer and coating

1. **PDMS Preparation**: Mix with curing agents at a **10:1** weight ratio.
2. **Incorporation of Fillers**: Add **ten wt%** of ZIF-8 and Silica-lite; ensure thorough mixing.
3. **Coating**: Coat optical fiber with the mixed matrix material.
4. **Curing**: Cure the coated fiber in a controlled environment.

## Future Work

- Conduct long-term testing to evaluate sensor stability in varying environmental conditions.
- Explore additional sensing materials compatible with reel-to-reel coating and demonstration of distributed sensing


**References**

1. https://pubs.acs.org/doi/abs/10.1021/acssensors.7b00808?ref=vi_sensors-and-industry
2. https://pubs.acs.org/doi/10.1021/acs.est.2c02723?ref=pdf



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