Fe-Coated Optical Fiber for Distributed Corrosion Monitoring in Soil and Aqueous Environments

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Disclaimer

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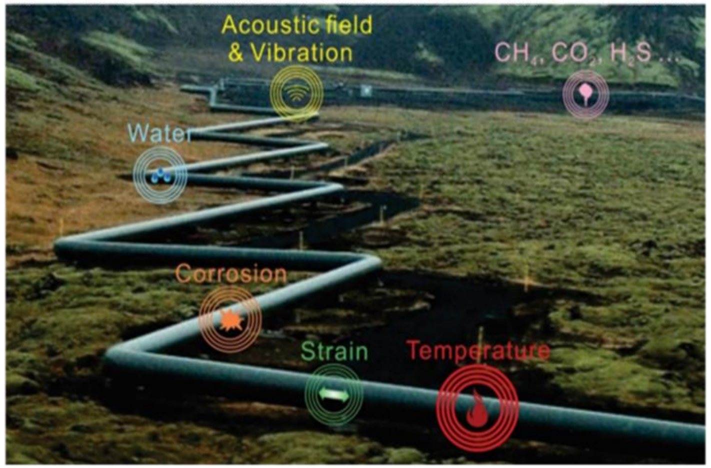
Outline

- **Introduction**
  - Background
  - Essence of optical fiber sensing
- **Key Objectives and Experimental**
- **Results and Discussion**
  - Monitoring factors causing corrosion (humidity and gases)
  - Intensity-based corrosion monitoring in aqueous environment
  - Transmission-based corrosion monitoring in aqueous environment
  - Corrosion monitoring in soil
- **Conclusions**
- **Acknowledgements**

Background



- Annual loss of ~$14.0 billion occurs due to corrosion across oil and gas pipelines and exploration
- Monitoring of corrosion requires identification and quantification of H_2O, CO_2, and H_2S
- Conventional monitoring techniques have limited capability to identify corrosion failures before they occur
- Therefore, real-time monitoring is needed to detect and mitigate pipeline risks

Sensors **2019**, 19, 3964.

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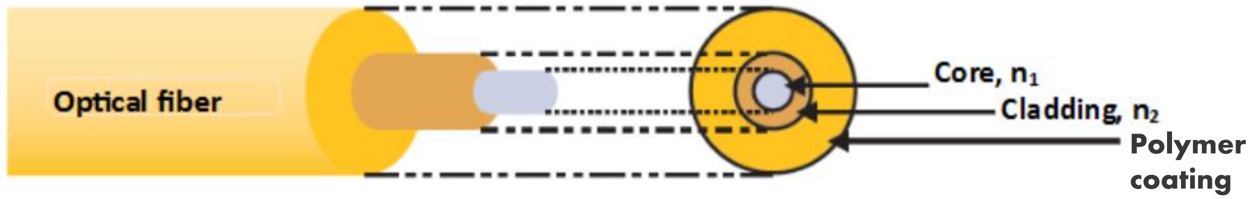
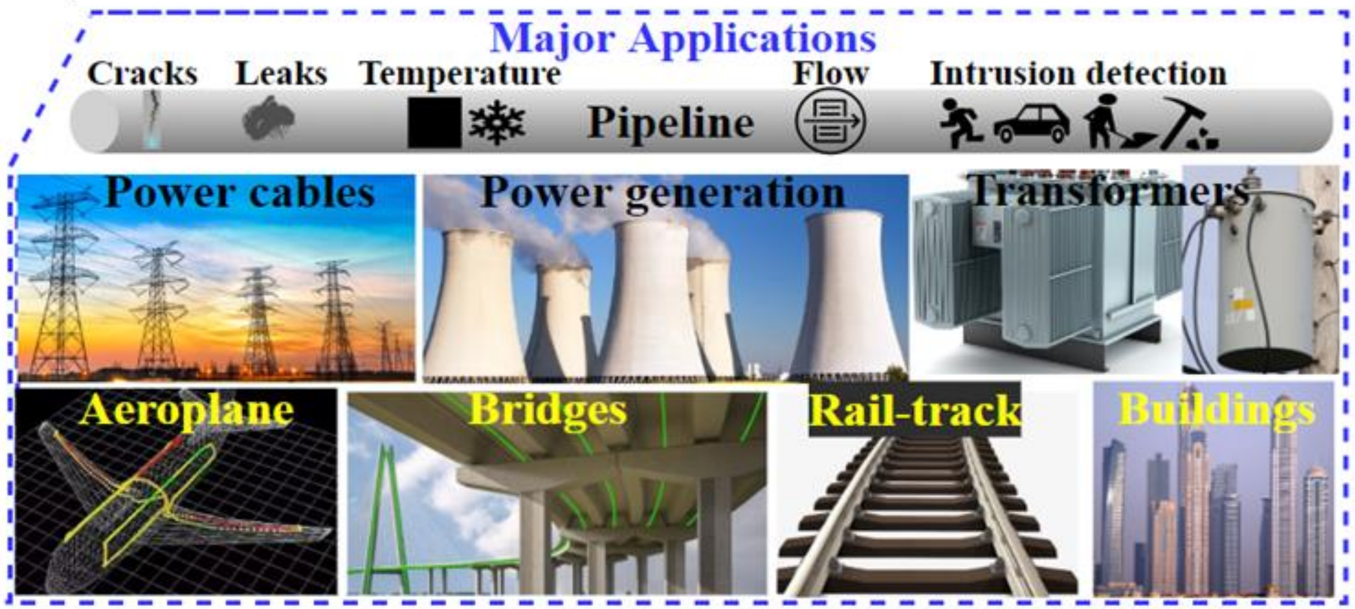
Optical Fiber Sensing





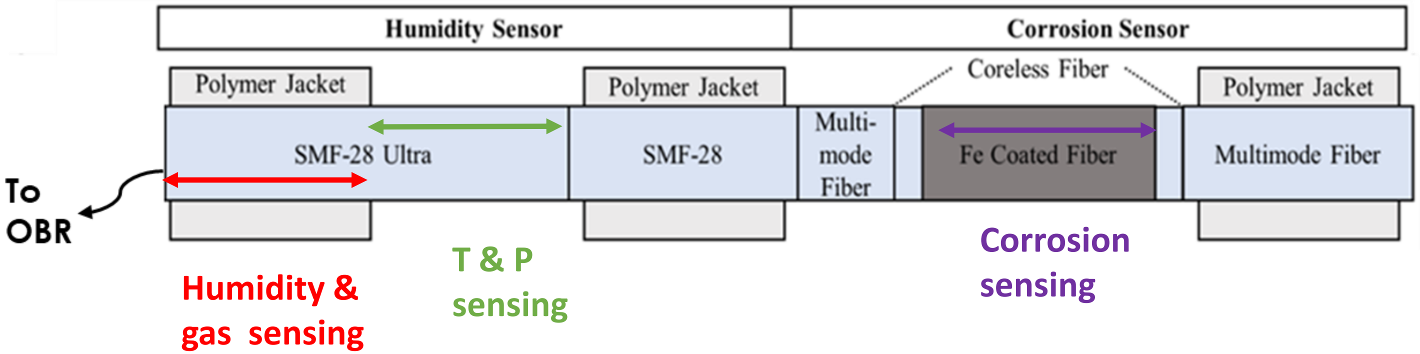
Advantages of optical fiber sensors (OFS):

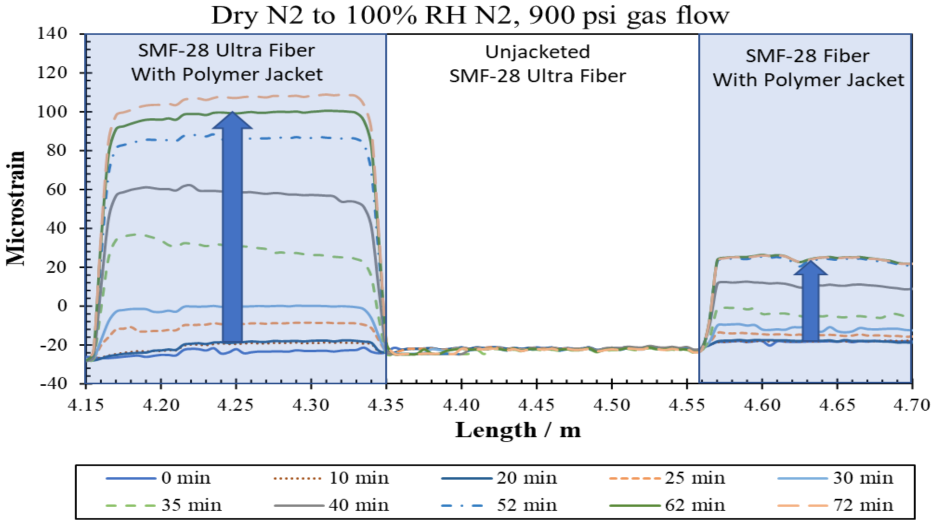
- Capable of nondestructive and in-situ distributed measurement
- Small size, lightweight, and flexible
- High sensitivity and accuracy
- Improved safety in the presence of inflammable gases
- Inherent immunity to electromagnetic interference
- Compatible with optical fiber data communication systems

Sensors **2019**, 19, 3964.
Optical Fiber Communications, Gerd Keiser, 2002.

Multi-Parameter OFS for Monitoring Humidity and Corrosion

Design of OFS for humidity and corrosion sensing





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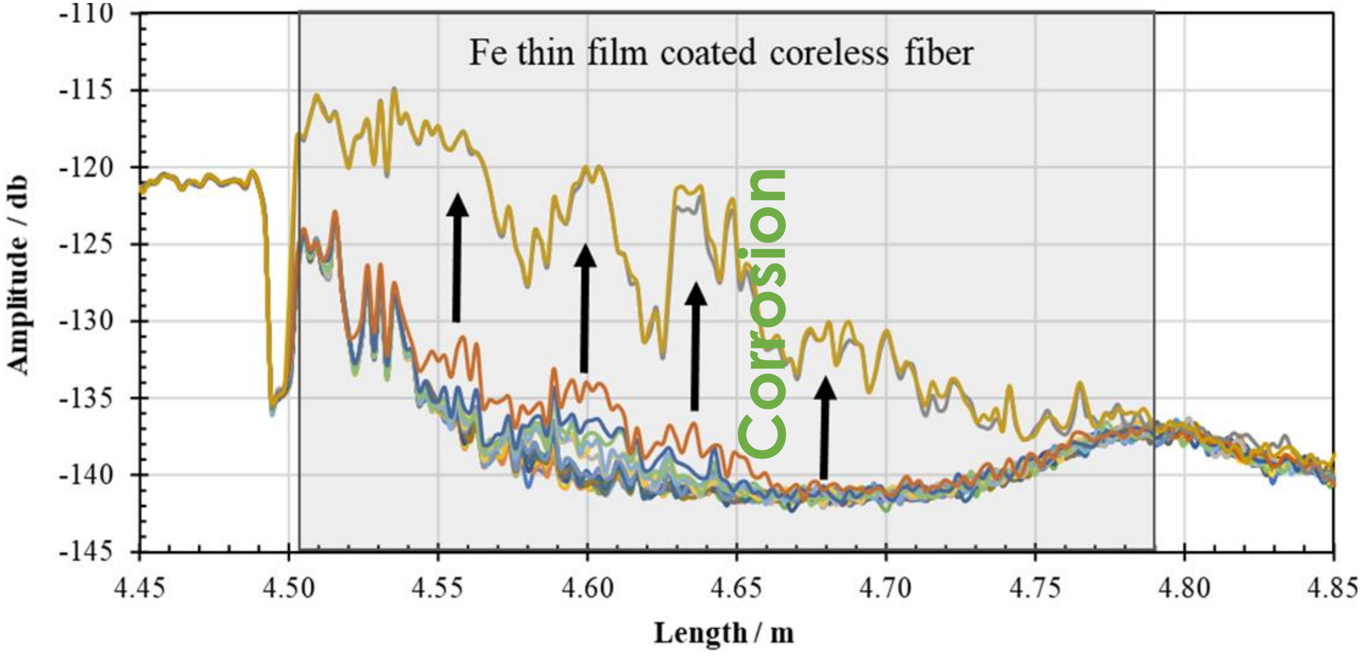
- Jacketed single mode fiber (SMF)-28 ultra undergoes swelling upon absorption of H_2O/gases resulting in strain development
- Humidity is monitored based on the strain developed along the jacketed SMF
- Unjacketed SMF is insensitive to humidity/gas sensing but sensitive to temp (T) and pressure (P)
- Fe-coated coreless fiber section acts as a corrosion sensor

Corrosion Sensing

100% RH CO_2



Backscattered light intensity amplitude along the Fe thin film-coated coreless fiber section in wet CO_2.

- Fe undergoes corrosion when exposed to corrosive environment (e.g., aqueous CO_2)

  Hydration-dissociation:

  $$2CO_{2(aq)} + 2H_2O_{(l)} \rightarrow 2H^+_{(aq)} + 2HCO_3^-{}_{(aq)}$$

  Anode:

  $$Fe_{(s)} \rightarrow Fe^{2+}{}_{(aq)} + 2e^-$$

  Cathode:

  $$2H^+_{(aq)} + 2e^- \rightarrow H_{2\,(g)}$$

- Corrosion is monitored based on the change in backscattered light intensity amplitude before and after corrosion of Fe

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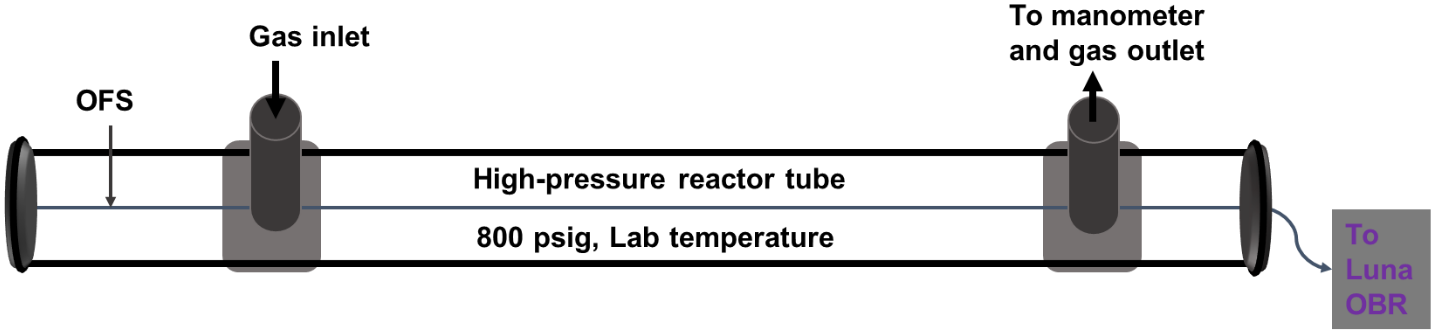
Key Objective and Experimental Setup-I

Objective A: Extending the capability of the OFS for calibrating strain response of SMF under controlled humidity and gas composition conditions



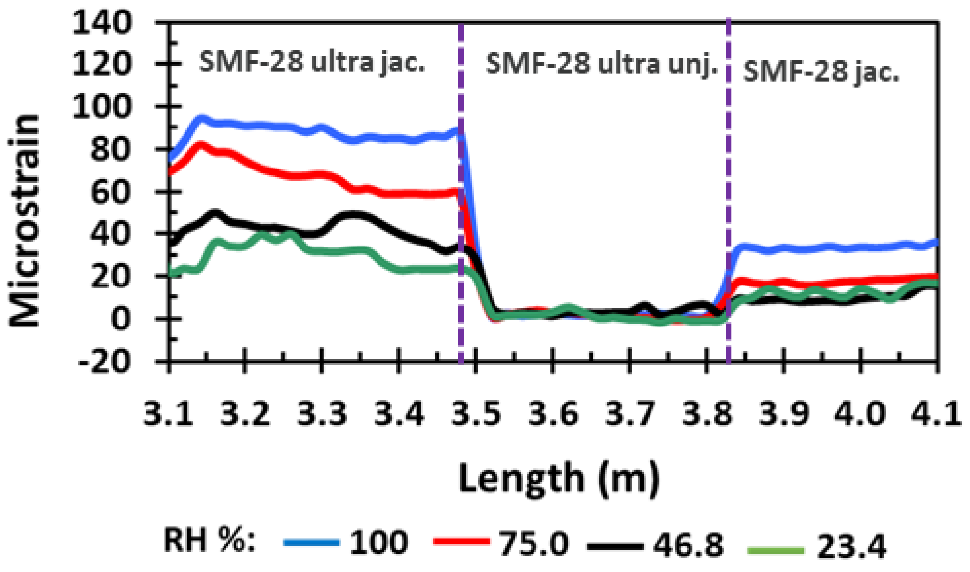
- Humidity was maintained by controlled dilution of 100% humid gas (N_2, CH_4, or CO_2) with respective dry gas (verified by humidity sensor)

  RH% studied: 100, 75.0, 46.8, and 23.4%

- Gas composition was maintained by proportional mixing of the respective gases based on their partial pressures

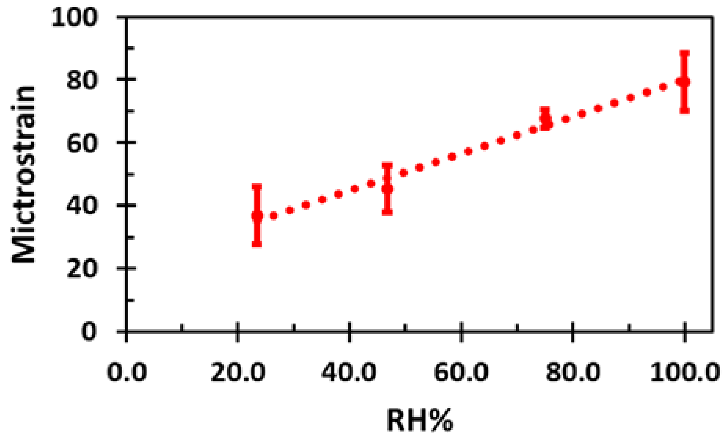
Microstrain Measurement for Monitoring Humidity/Gases

Microstrain with change in RH%



Reference trace: 800 psig dry N_2.

- Microstrain was measured under equilibrium (1 hr)
- Microstrain increases with increasing RH%

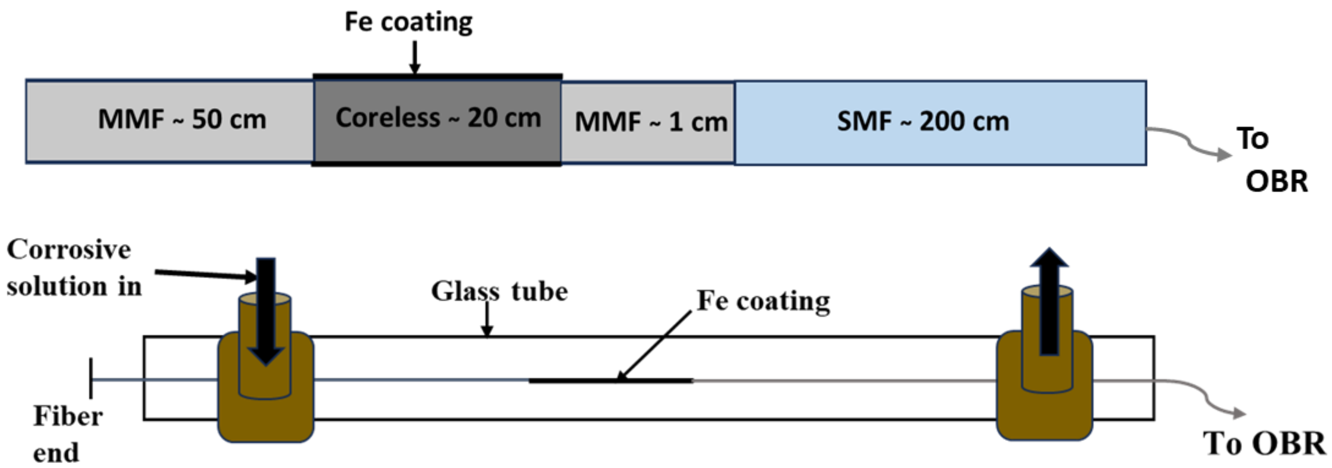


- Calibration curve shows good linear response of microstrain with RH% change (R^2 = 0.998)

CO_2 and CH_4 under different RH% and gas composition conditions were monitored similarly.

Key Objective and Experimental Setup-II

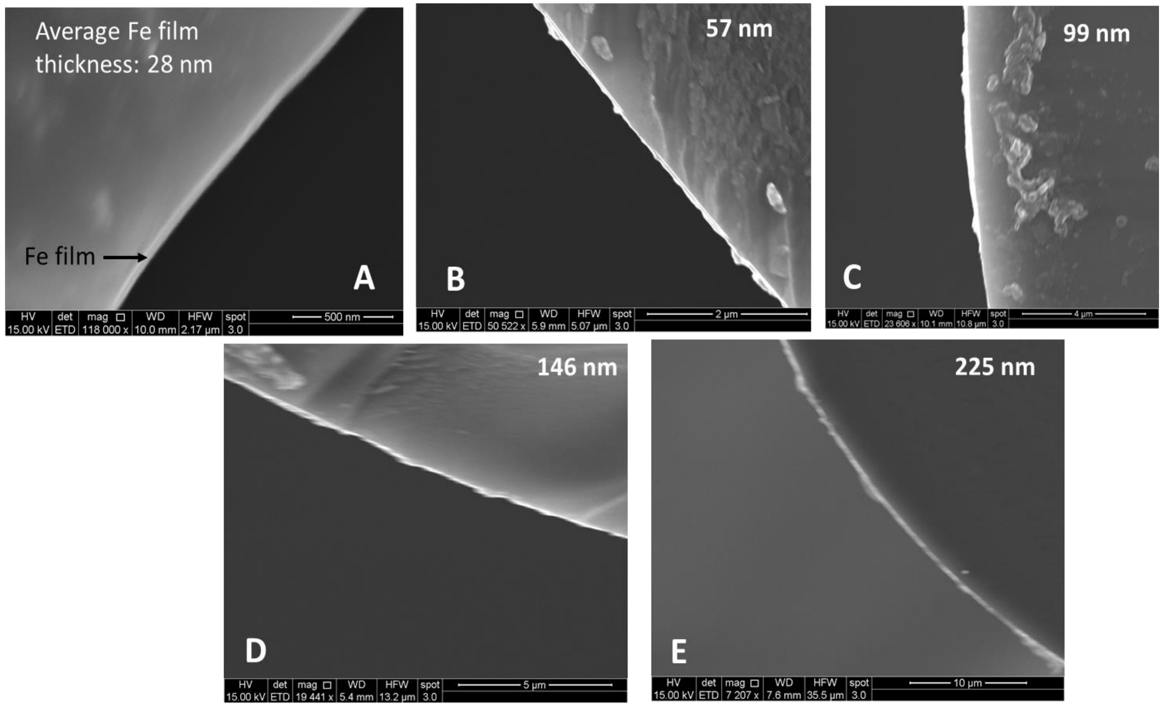
Objective B: Extending the capability of the Fe-coated OFS for monitoring accelerated corrosion rates in aqueous environment



- Electroless coating of a thin Fe film onto the coreless fiber section with controlled film thickness (~25-225 nm)
- Corrosion was studied in CO_2 saturated 3.5% aq. NaCl + HCl, pH = 3.2
- Corrosion rate of Fe = $\frac{\text{Fe film thickness (nm)}}{\text{Time for attaining steady state backscattered intensity amplitude of the light upon complete corrosion of Fe (min)}}$

Monitoring Corrosion

Coating of Fe film on the OFS surface



SEM images of the cross-section of the Fe-coated OFS prepared by the electroless coating.

- Performed electroless coating of Fe on to the OFS surface with variable coating thickness by immersing the fiber into the coating bath for different times:
  1 min: 28 nm
  2 min: 57 nm
  3 min: 99 nm
  4 min: 146 nm
  5 min: 225 nm

Corrosion Sensing: Monitoring Corrosion Rate

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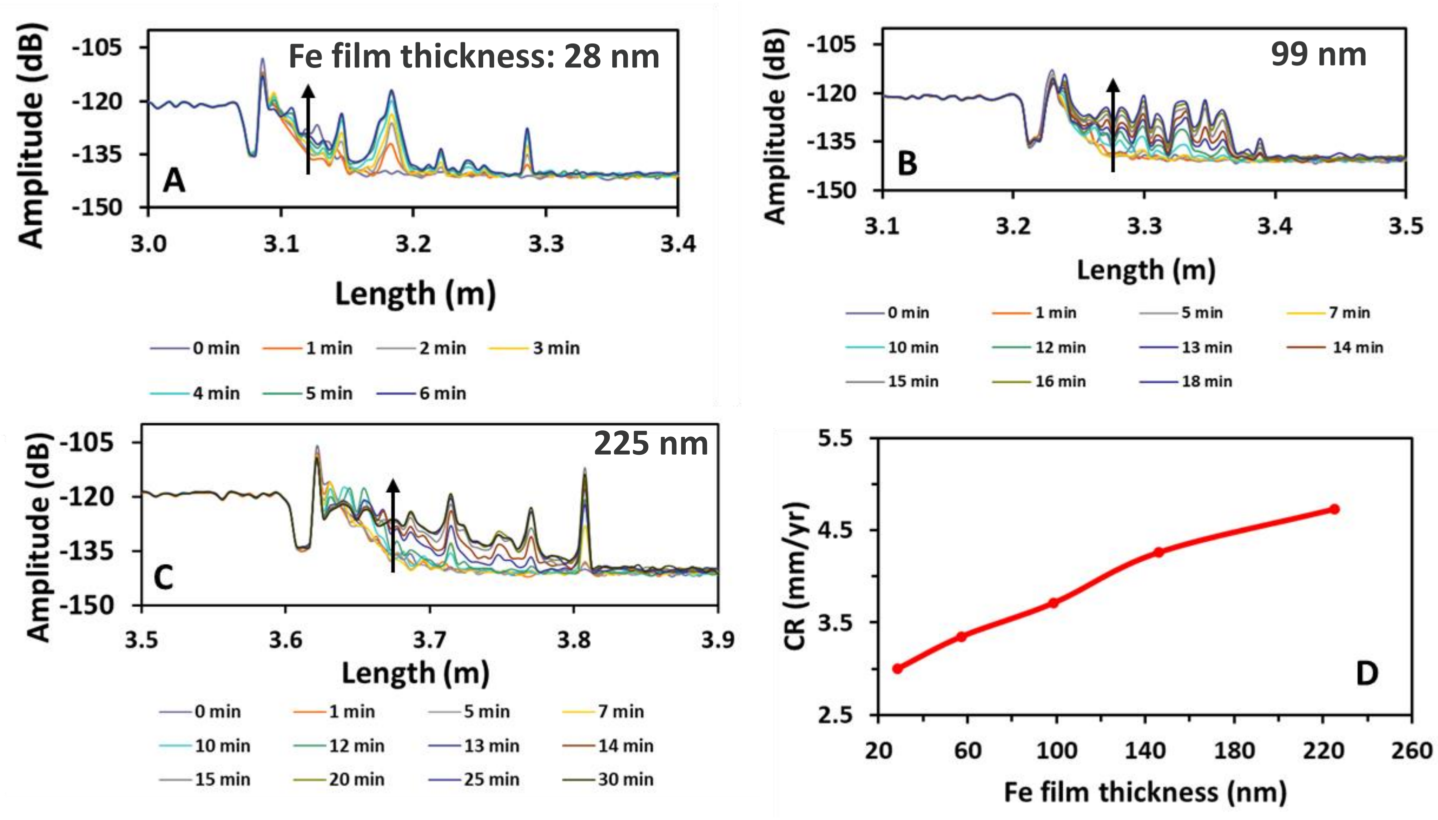
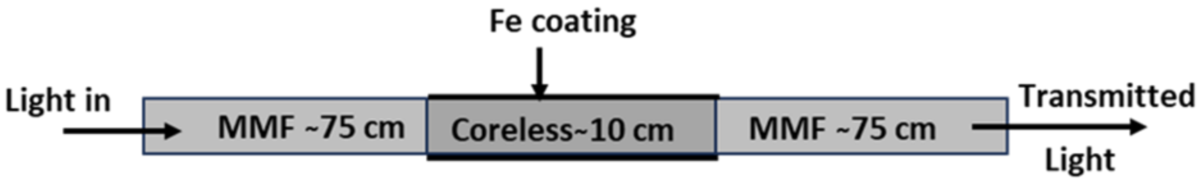
Changes in backscattered intensity amplitude of light along Fe-coated OFS section



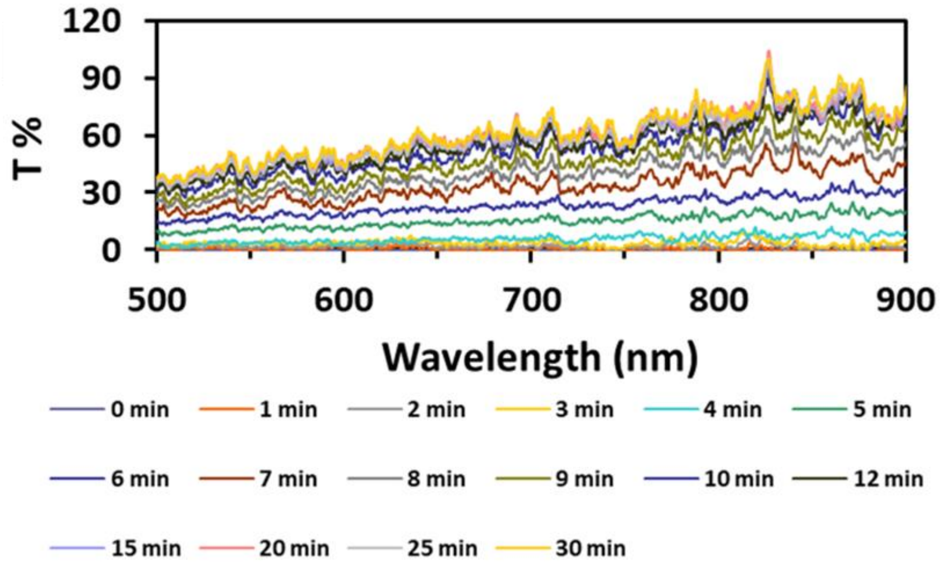
- Rate of change of Fe film thickness over time provides corrosion rate (CR)
- CR increases with increasing Fe film thickness, possibly due to rougher film surface at higher thickness

Corrosion was studied in CO_2 saturated aqueous 3.5% NaCl + HCl, pH 3.2.

Corrosion Monitoring via Transmission Measurement



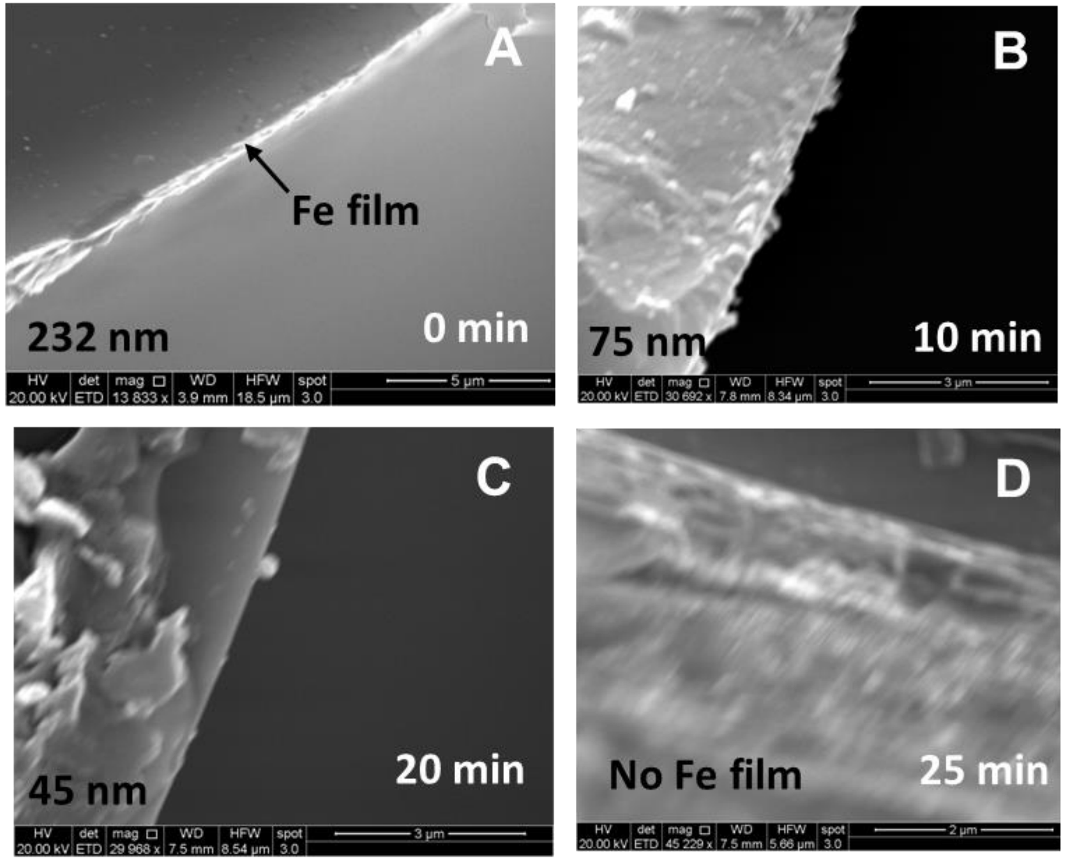
Design of experiment for monitoring corrosion of Fe in transmission mode.

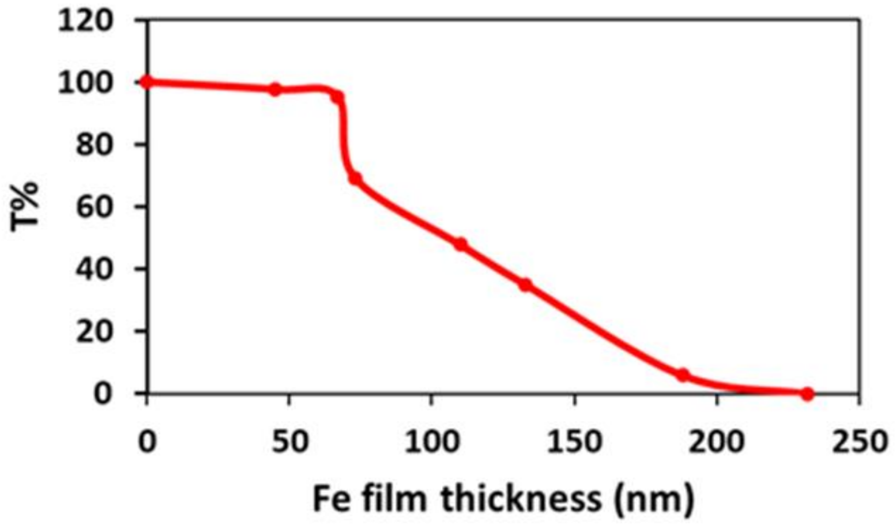


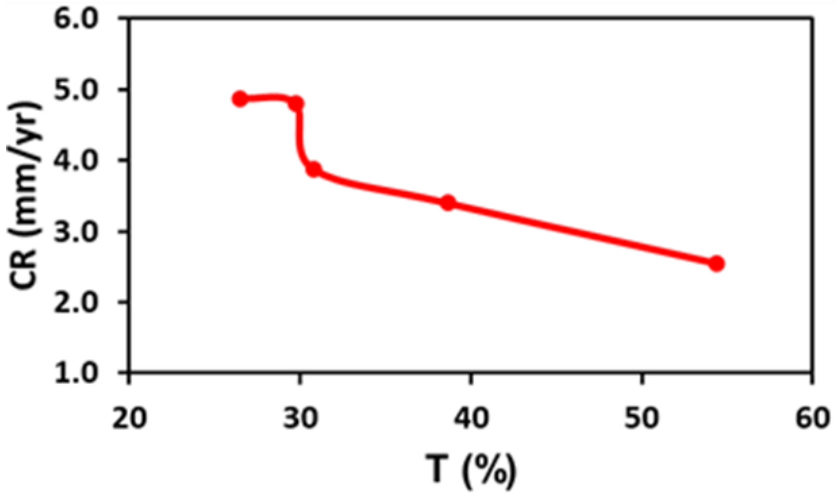
Normalized transmission (T%) of light in the visible range (500–900 nm) with time during corrosion of Fe.

- Fe absorbs visible light
- Transmission of light increases with decrease in Fe film thickness due to corrosion
- Change in light transmission rate measures CR

Correlating Corrosion Rate with Transmission



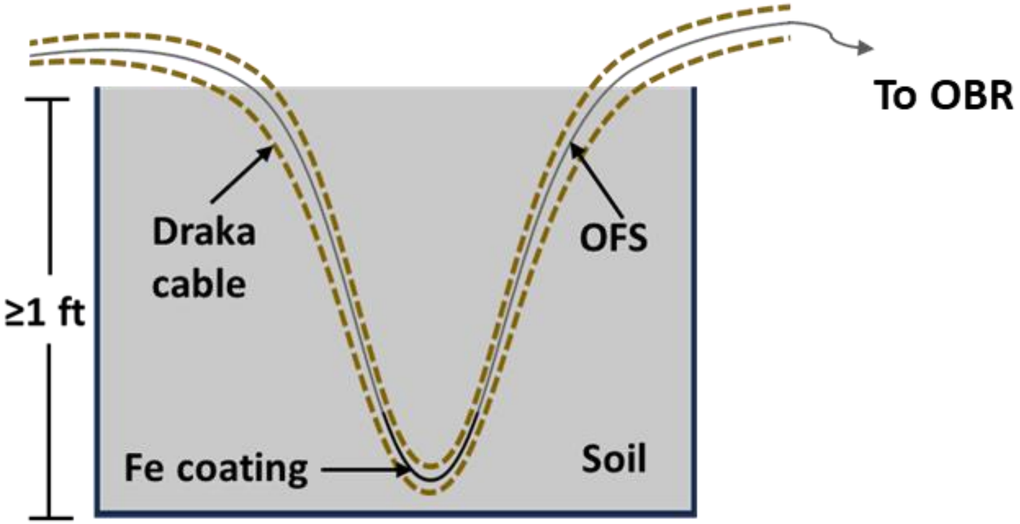


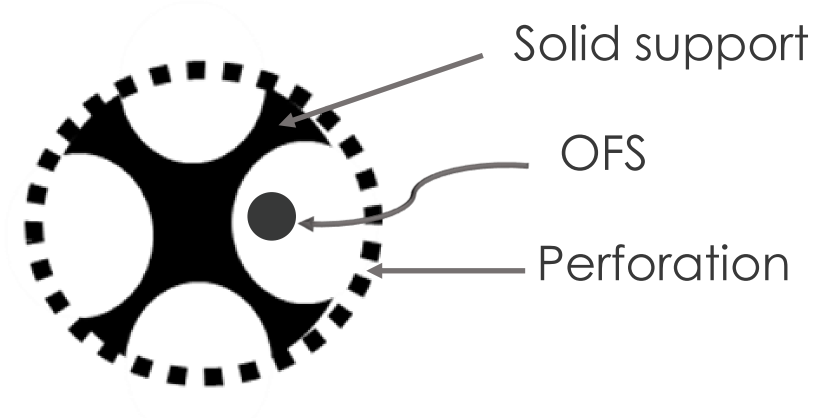


Decrease of film thickness of Fe coated onto the OFS with time immersed in corrosive solution.

Key Objective and Experimental Setup-III

Objective C: Extending the capability of the Fe-coated OFS for monitoring corrosion in soil

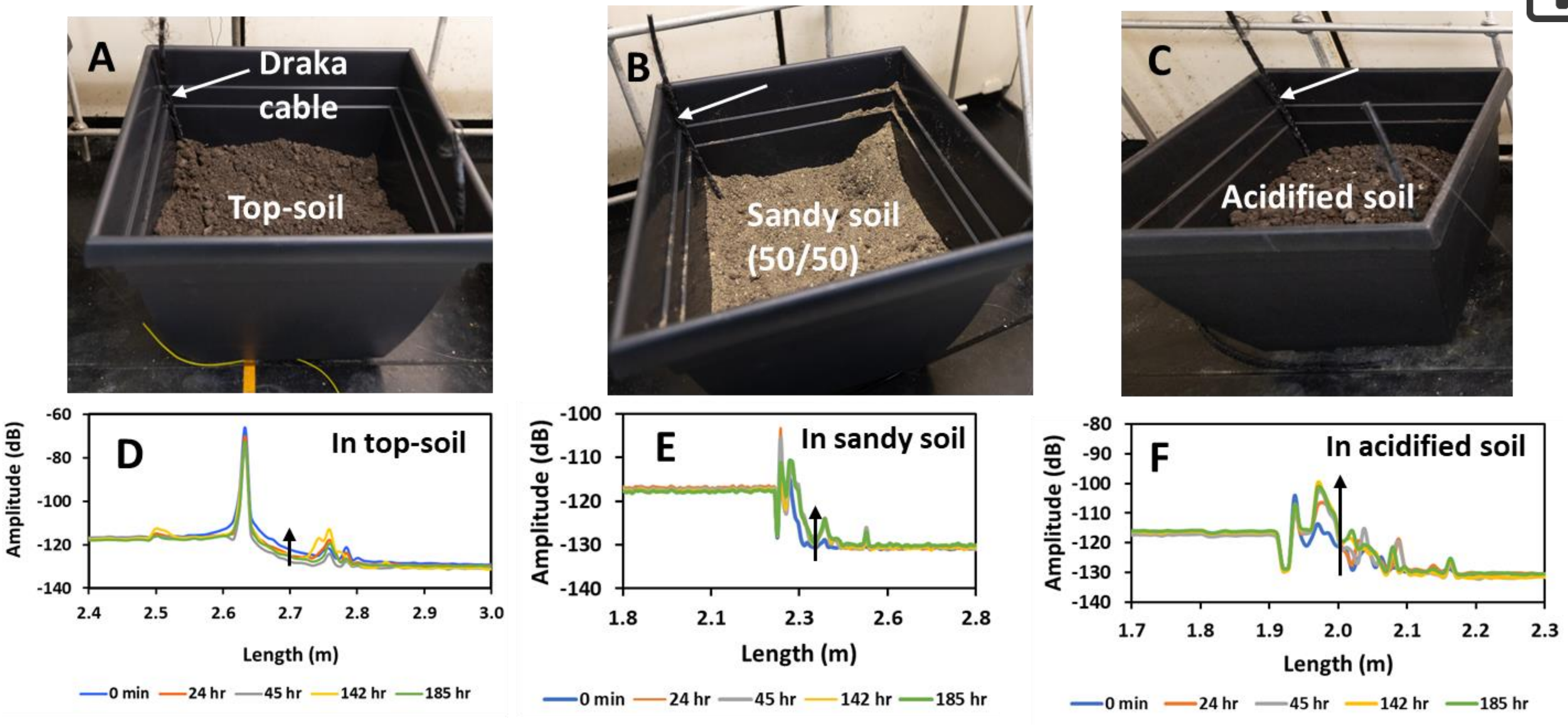




Cross-section view of Draka cable with OFS.

- Soil provides stress to the OFS rendering it susceptible to mechanical disturbance or breakage
- Draka cable provides physical support to the relatively fragile OFS and also allows exposure of the sensor to the outside environment

Corrosion Monitoring in Soil



- Types of soil used for the corrosion experiment: (A) top-soil, (B) sandy soil, and (C) acidified soil
- Draka cable provides physical support for burying the fiber sensor in soil
- CR: highest in acidified soil, moderate in sandy soil, and least in topsoil

Conclusions

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- Optical fiber sensors provide long distance distributed sensing of humidity, CH_4, and CO_2 in natural gas pipeline relevant conditions.
- Corrosion was successfully monitored by using Fe-coated OFS, where Fe acts as a corrosion proxy.
- Accelerated corrosion rate was monitored by measuring the rate of change of backscattered light intensity amplitude during corrosion of Fe exposed to the corrosive aqueous environment.
- Physical protection of the OFS by a solid support such as a Draka cable enabled corrosion monitoring in soil.

18

Acknowledgments

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