Multi-Parameter Optical Fiber for Distributed Sensing of Humidity, CH_4, CO_2, and Corrosion

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Background

- Natural gas transmission pipelines are mainly composed of Fe/steel and are prone to undergo corrosion under operating conditions.
- Corrosion in the natural gas transmission pipelines occurs through condensation of water droplets onto the pipe interior together with dissolution of contaminants such as CO_2, H_2S, and salts.
- Corrosion causes approximately $1.4 billion/yr of economic loss in the U.S.
- Identifying and quantifying the factors causing corrosion and its real-time monitoring is important for effective and safe pipeline operation.

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Advantages of Optical Fiber Sensors:

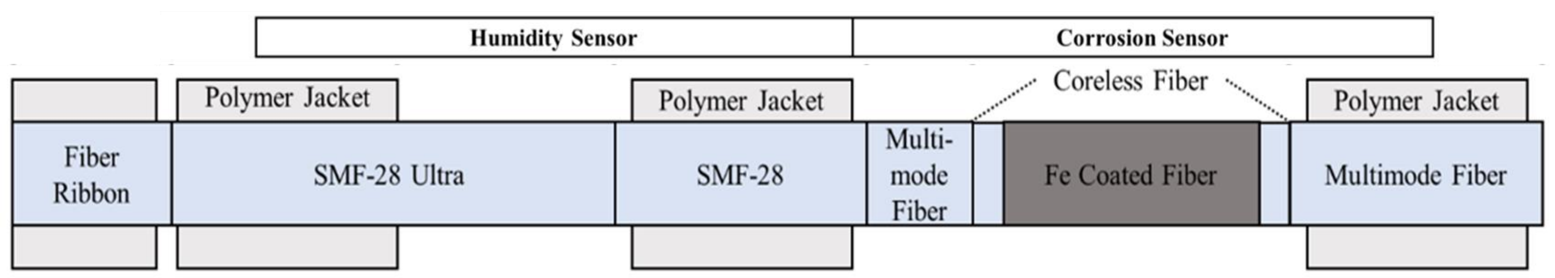
- Recently, optical fiber-based sensing approaches have been widely explored due to its advantages of small size, light weight, flexibility, improved safety in the presence of flammable gases, and long-range and distributed sensing capabilities.

Proposed Optical Fiber Sensing for Pipelines

- The polymer jacket of single-mode fiber (SMF) undergoes strain changes due to absorption of H_2O and gases which can serve as a sensing layer.
- Fe coated onto the coreless fiber section spliced together with multi-mode fiber (MMF) serves as a corrosion proxy to the pipeline wall.
- Upon exposure to a corrosive environment such as an acid (H^+), Fe undergoes electrochemical dissolution (corrosion) alongside hydrogen evolution.

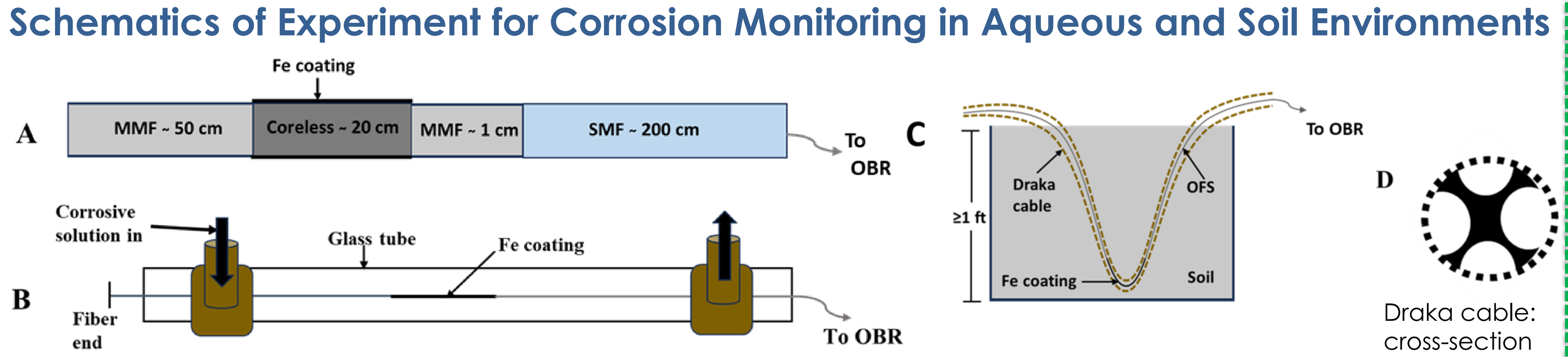
$$Fe_{(s)} \longrightarrow Fe^{2+}_{(aq)} + 2e^- \qquad H^+_{(aq)} + 2e^- \longrightarrow H_{2\,(g)}$$

Designing of a Single Optical Fiber with Multiple Functions



- Corrosion of Fe coated onto the coreless fiber section is detected based on the increase in amplitude of backscattered light intensity amplitude of the light being passed as Fe undergoes corrosion.

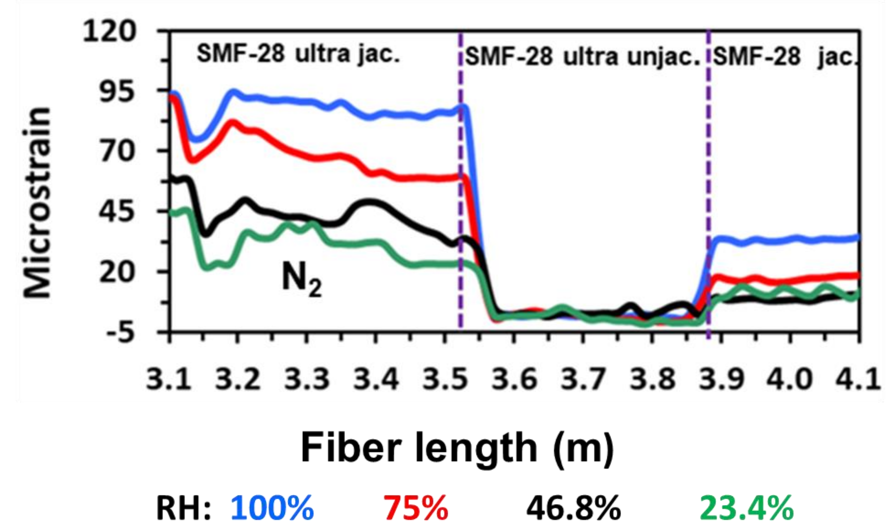
Schematics of Experiment for Corrosion Monitoring in Aqueous and Soil Environments



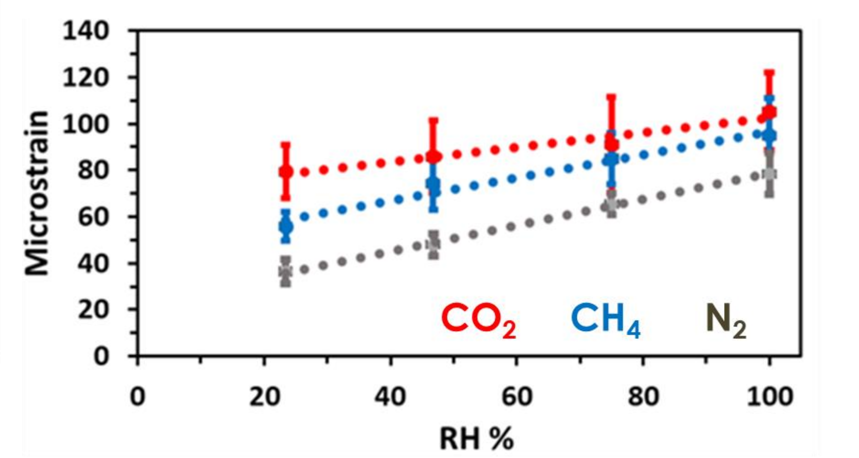
Draka cable: cross-section

Strain-Based Sensing of Humidity and Gases

Microstrain change with change of RH in N_2



Calibration curve with N_2, CH_4, and CO_2



Microstrain under equilibrium measured along SMF-28 ultra of the optical fiber sensor (OFS) under different gas composition and RH conditions

RH%	Microstrain Under Different Gas composition								
	N_2 Composition(%)	CH_4 Composition Mixed with N_2 (%)				CO_2 Composition Mixed with N_2 (%)			
	100	23.4	46.8	75.0	100	23.4	46.8	75.0	100
0	0	13.2	16.9	22.9	26.0	28.8	43.5	62.0	72.4
23.4	36.4	41.5	42.0	49.9	55.8	63.8	59.8	63.1	79.4
46.8	48.0	46.7	61.7	-	74.3	53.7	74.0	-	85.8
75.0	65.4	69.9	-	74.5	85.0	69.2	-	82.5	91.1
100	78.3	-	-	-	94.9	-	-	-	105.2

Microstrain Under Mixed Gas Composition	
Gas Composition	Microstrain
25% RH N_2 + 25% dry CH_4 + 50% dry CO_2	70.1
25% RH N_2 + 50% dry CH_4 + 25% dry CO_2	63.0
50% RH N_2 + 25% dry CH_4 + 25% dry CO_2	61.1
25% dry CH_4 + 75% dry CO_2	64.0
50% dry CH_4 + 50% dry CO_2	55.2
75% dry CH_4 + 25% dry CO_2	39.1

Summary of linear regression statistical analysis of the microstrain dataset

Independent Variable	Coefficients	Standard Error (%)	t-Stat	P-Value	Linearity
H_2O	a = 1176.5	6.4	15.5	8.81×10^{-18}	R^2= 0.959
N_2	b = 21.8	13.2	7.60	5.09×10^{-9}	
CH_4	c = 37.3	7.9	12.7	6.43×10^{-16}	
CO_2	d = 67.9	3.1	21.8	9.96×10^{-23}	

Total microstrain = a*H_2O + b*N_2 + c* CH_4 + d*CO_2

Order of coefficient of independent variables:
$H_2O >> CO_2 > CH_4 > N_2$

Polarity order ($H_2O >> CO_2 > CH_4 \approx N_2$) & Molecular size order ($CH_4 > CO_2 > N_2 > H_2O$)

↓↓

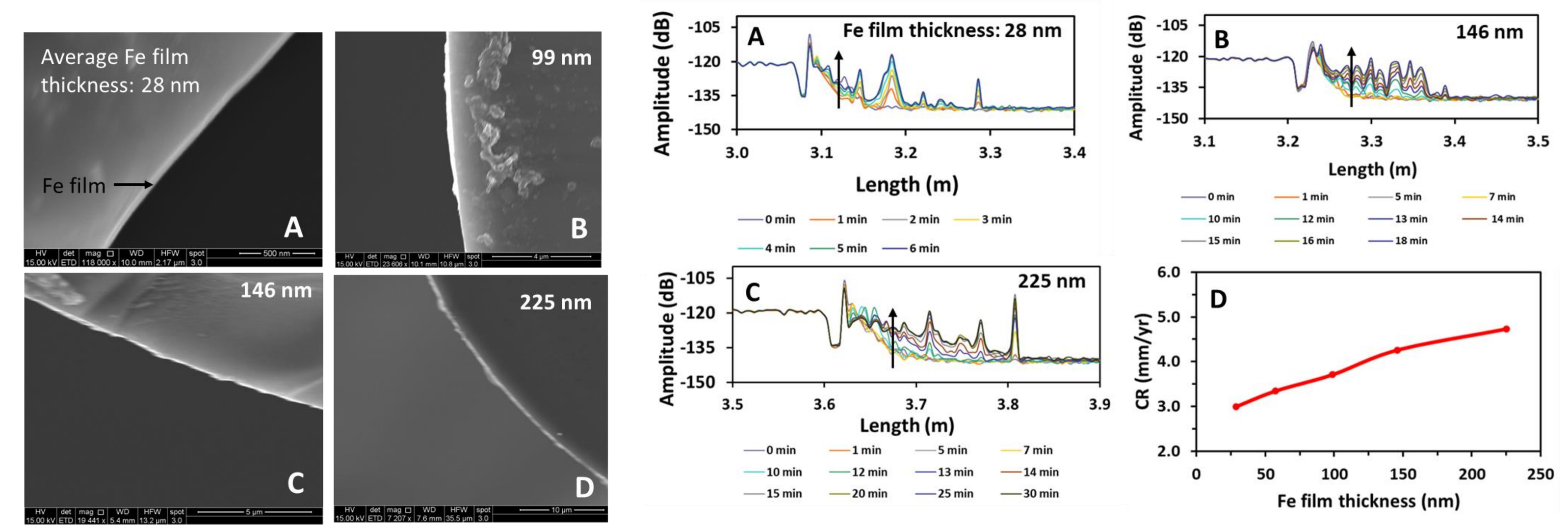
Determine absorption coefficients

- Microstrain along the jacketed SMF (SMF-28-ultra) increases with increasing mole fraction of H_2O, CH_4 and CO_2 when mixed with N_2.
- H_2O carries significantly higher absorption coefficient per molar unit compared to CO_2, CH_4 and N_2 likely due to its highest polarity and smallest size.

Conclusions

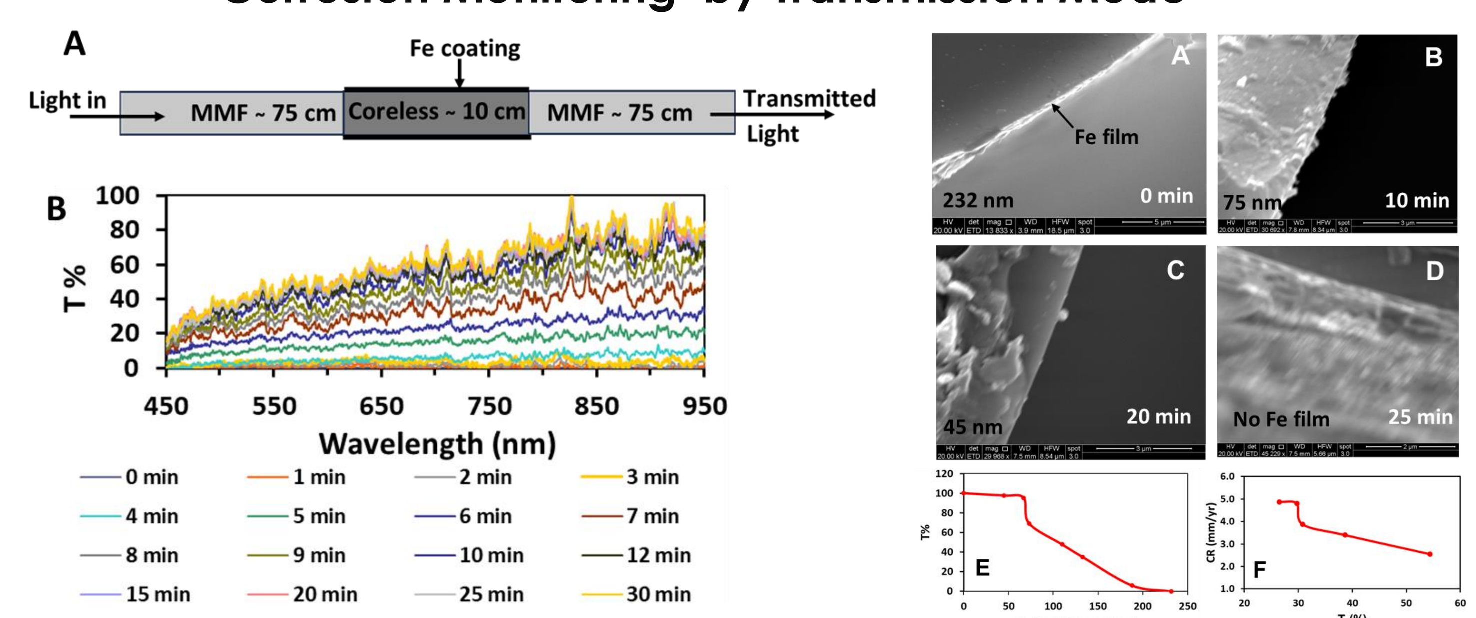
- Successfully demonstrated use of optical fiber sensors for monitoring humidity, CH_4, CO_2, and corrosion in natural gas pipeline relevant conditions.
- Linear regression analysis of the microstrain dataset enables assigning absorption coefficients of H_2O and other gases to the polymer material of the fiber sensor.
- Fe-coated coreless fiber section acts as a corrosion sensor where the corrosion rate for different Fe film thickness was successfully measured.
- The corrosion rate of Fe increased with increasing film thickness (28-225 nm range) and the result is supported by corrosion monitoring in transmission mode.
- Successfully monitored corrosion of Fe under soil by using Fe-coated fiber sensor which was reinforced by the Draka cable for mechanical support during installation in soil.

Amplitude-Based Corrosion Monitoring in Aqueous Environment



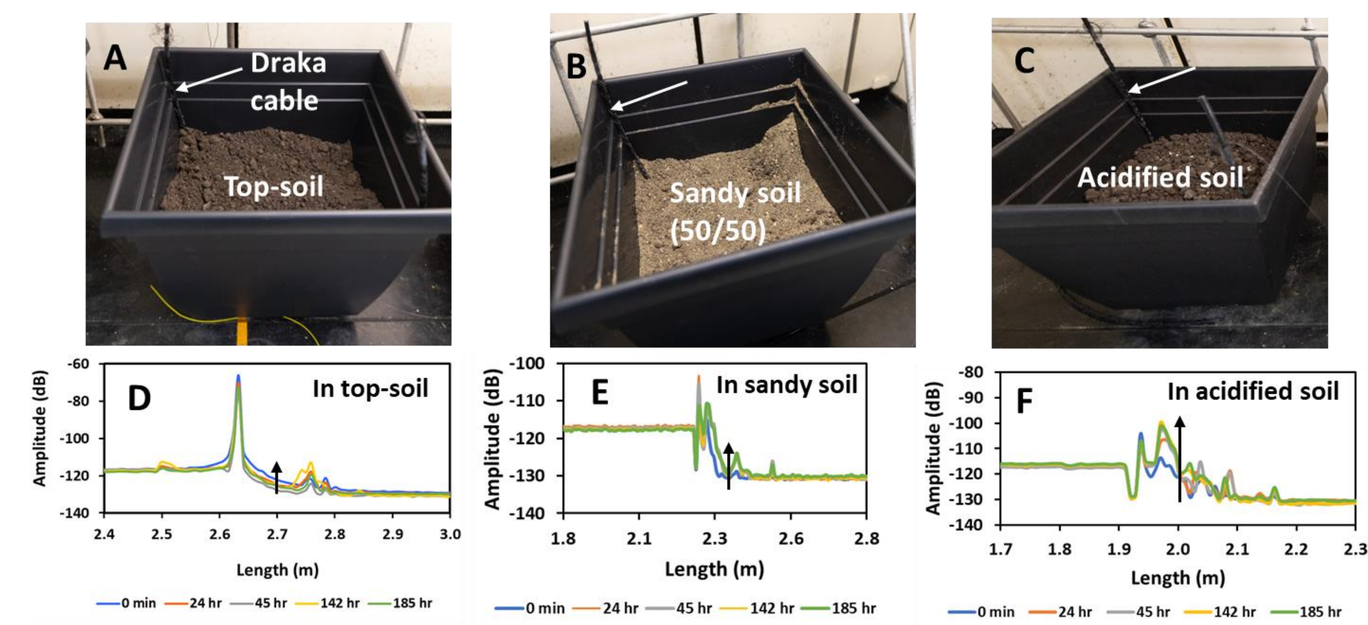
- Scanning electron microscopy allows measurement of Fe film thickness deposited onto the optical fiber sensor.
- Corrosion causes changes in backscattered light intensity amplitude as measured by optical backscattered reflectometer (OBR).
- Corrosion rate increases with the Fe film thickness.

Corrosion Monitoring by Transmission Mode



- Transmission of light increases as Fe undergoes corrosion and is saturated once corrosion is complete.
- Observed similar corrosion rate (4.7 mm/yr for 225 nm Fe film) between the measurements by the OBR and the transmission mode.

Corrosion Monitoring in Soil



- Deployed and installed Fe-coated fiber sensor which was reinforced by the Draka cable in soil ≥1 ft.
- Corrosion was fastest in acidified soil, moderate in sandy soil, and slowest in top-soil.