Metallic Coating Enabled Optical Fiber Sensor for Distributed Corrosion Monitoring

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NATIONAL ENERGY TECHNOLOGY LABORATORY

Ruishu Wright
Research Scientist
Research & Innovation Center

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Authors and Contact Information

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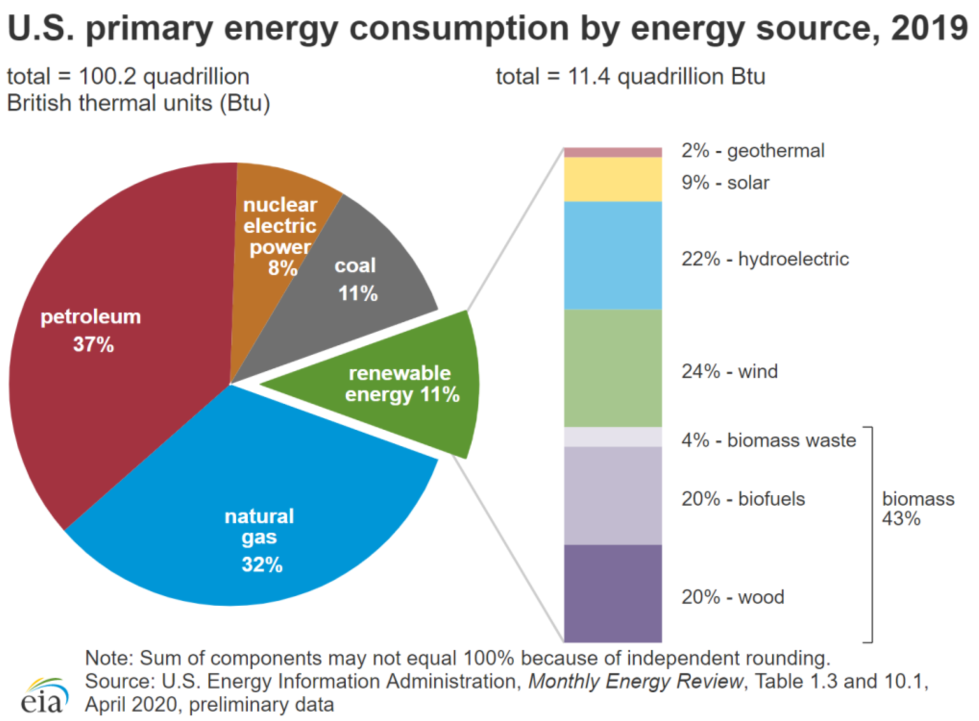
Ruishu F. Wright[a,b], Nathan Diemler[a,b], James C. Egbu[c], Michael P. Buric[d], Paul R. Ohodnicki, Jr.[e]

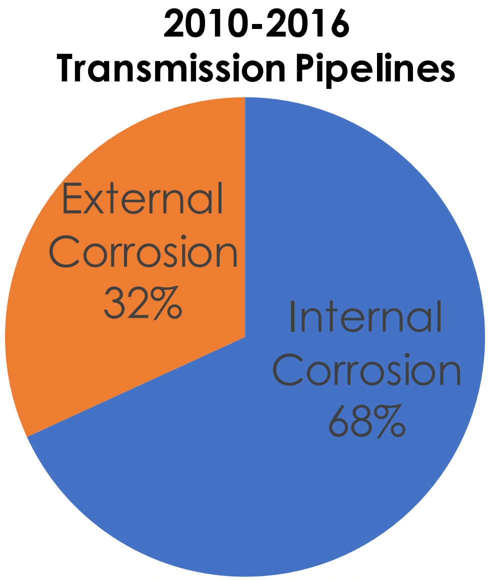
[a]National Energy Technology Laboratory, 626 Cochrans Mill Road, Pittsburgh, PA 15236, USA;
[b]NETL Support Contractor, 626 Cochrans Mill Road, Pittsburgh, PA 15236, USA;
[c]Department of Materials Science and Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA;
[d]National Energy Technology Laboratory, 3610 Collins Ferry Road, Morgantown, WV 26507, USA;
[e]Department of Mechanical Engineering and Materials Science, University of Pittsburgh, Pittsburgh, PA 15261, USA.

Outline

- Research background
- Experimental setup
- Results and discussion
- Conclusions
- Disclaimer

Corrosion in Oil and Gas Infrastructure





- $1.4 billion annually: direct corrosion costs in domestic oil and gas exploration and production in the U.S.
- $589 million: surface piping and facility costs
- $463 million: downhole tubing expenses
- $320 million: capital expenditures related to corrosion.
- **25-30% can be saved** with optimal corrosion management.

Corroded production casing pipe sample from downhole

(University of North Dakota Energy & Environmental Research Center)

Koch, G. H., Brongers, Michiel, P. H., Thompson, N. G., Virmani, Y. P. and Payer, J. H., "Corrosion costs and preventive strategies in the United States" (2002).

Corrosion is an Electrochemical Process Causing Mass Loss and Structural Deterioration

Dissolution of CO_2: $CO_2(g) \leftrightarrow CO_2(aq)$

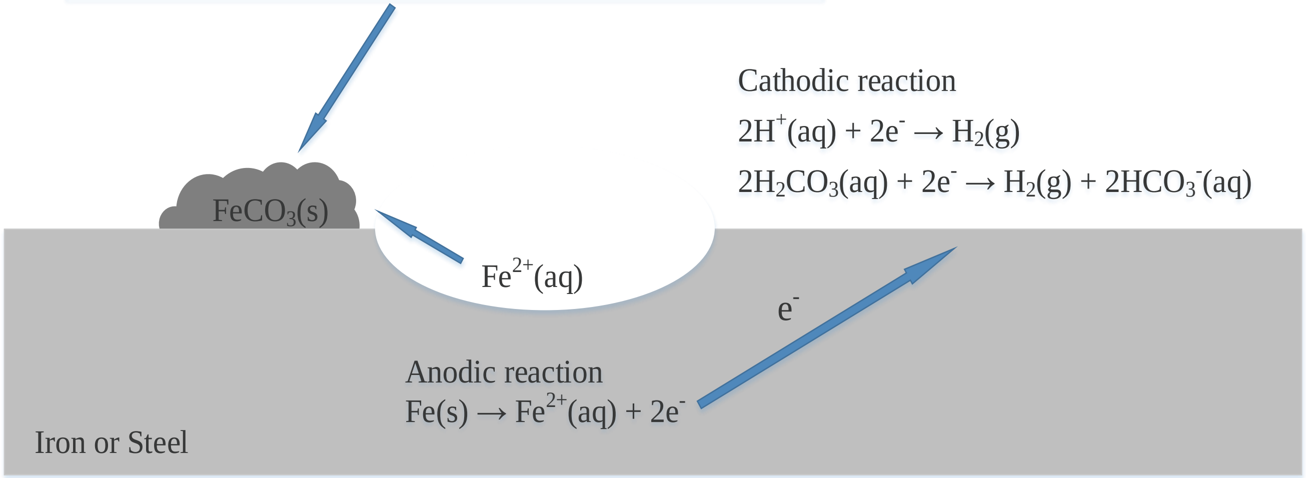
Hydration of CO_2: $CO_2(aq) + H_2O(l) \leftrightarrow H_2CO_3(aq)$

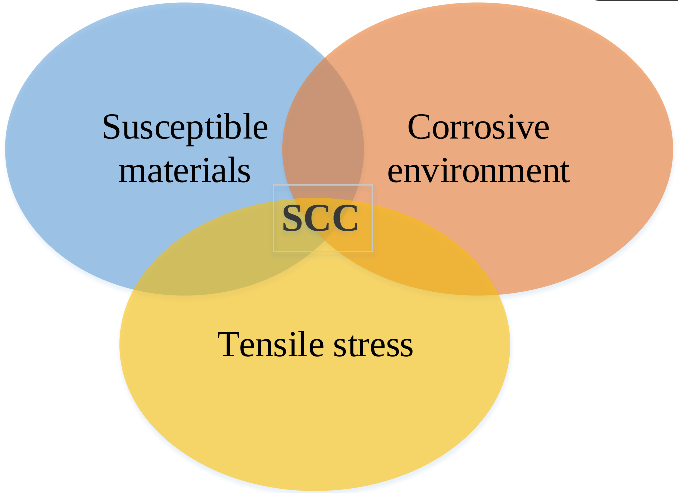
~ 0.2% of $CO_2(aq)$ and quite slow

Dissociation of $H_2CO_3(aq)$:

$H_2CO_3(aq) \leftrightarrow H^+(aq) + HCO_3^-(aq)$, pK_1=6.35 at 25 °C

$HCO_3^-(aq) \leftrightarrow H^+(aq) + CO_3^{2-}(aq)$, pK_2=10.33 at 25 °C

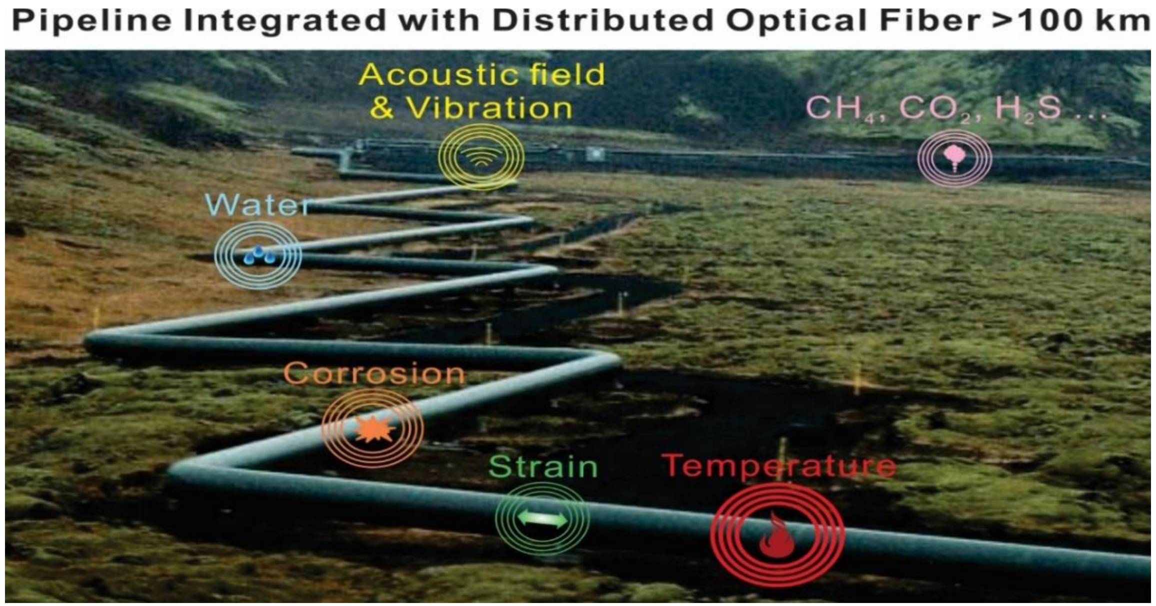


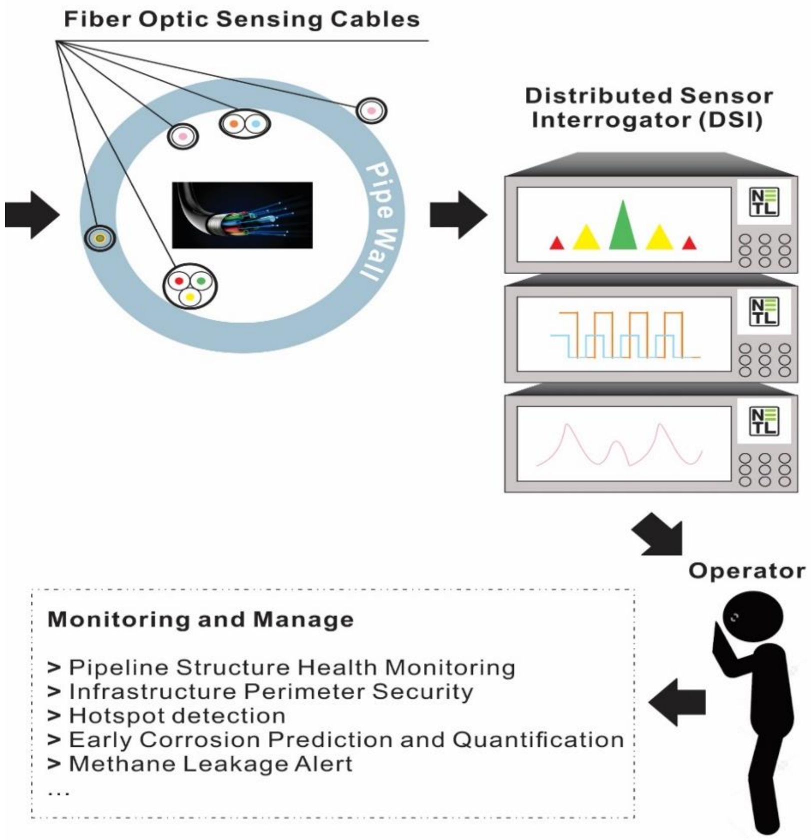


https://corrosion.ksc.nasa.gov/stresscor.htm

Jones, D. A., Principles and Prevention of Corrosion, P 237.
Han, J., Nesic, S., Yang, Y., Brown, B., Electrochimica Acta, 2011, 5396-5404.

Optical Fiber Sensor Platform for Natural Gas Pipelines





- Early Corrosion Onset Detection
- Methane Leak Detection

A Multi-Parameter, Distributed Optical Fiber Sensor (OFS) Platform Enabling Reliability & Flexibility

Target Metrics = >100km Interrogation, <1m Spatial Resolution

Distributed OFS Sensing Using Optical Backscatter Reflectometer (OBR)

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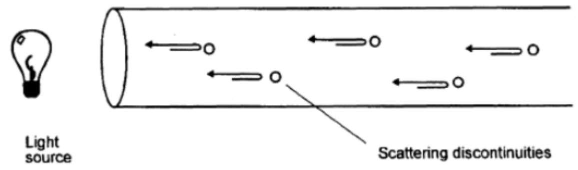
OBR measures the Rayleigh backscattering from the fiber-under-test (FUT).



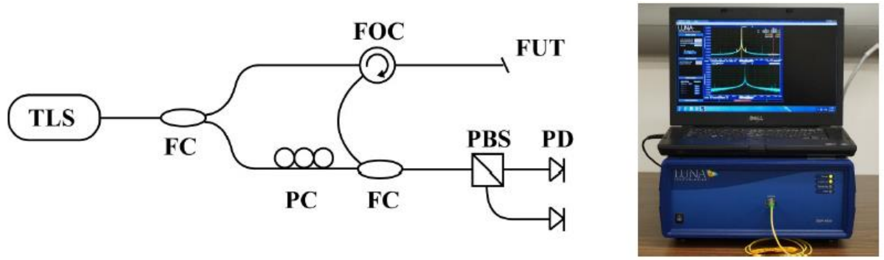
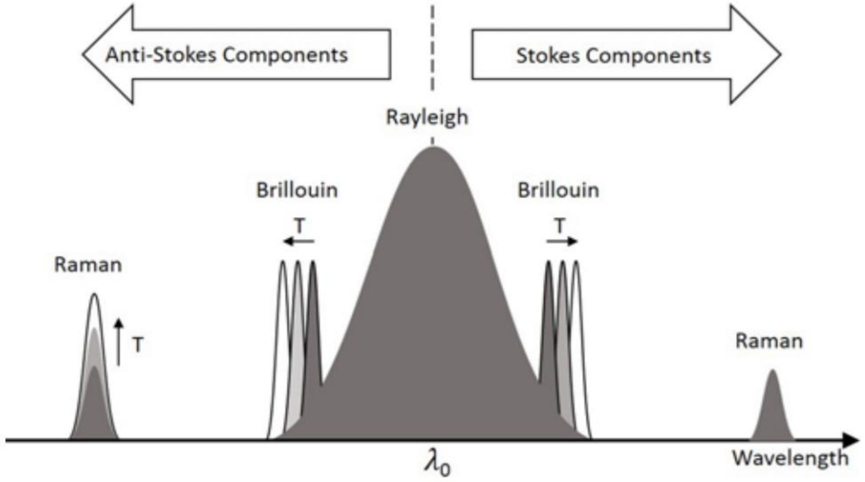


Figure 1 – LUNA OBR 4600 distributed interrogator LEFT: internal components (TLS: tunable laser source, FC: fiber coupler, FOC: fiber optic circulator, PC: polarization controller, PBS: polarizing beamsplitter, PD: photodiode); RIGHT: photo of instrument.

Backscattering enables distributed temperature, strain, and acoustic sensing (DTS, DSS, DAS)

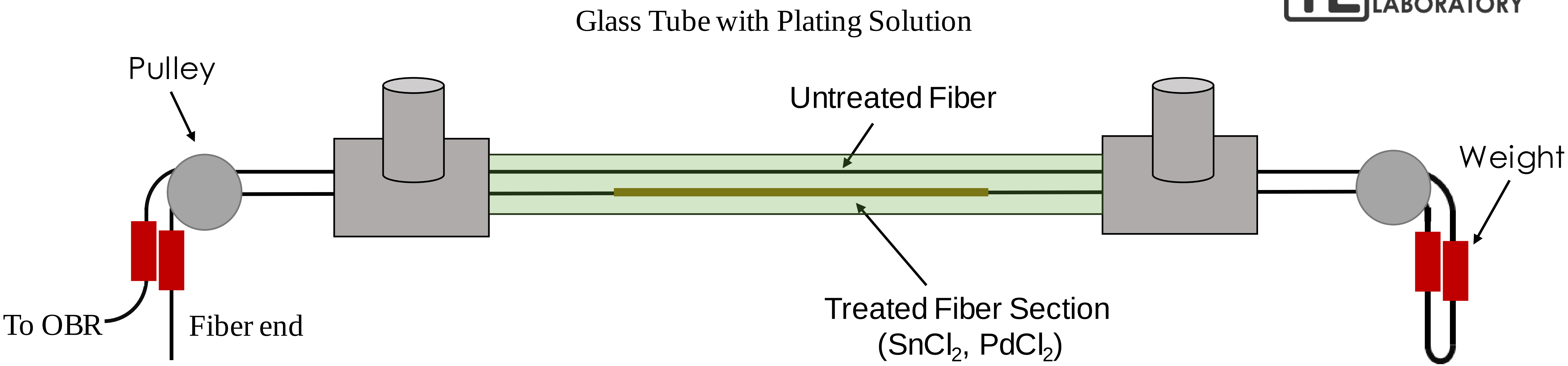


OBR can measure spatial profiles of either temperature or strain changes

$$\text{Temperature Change} = \Delta T = -\frac{\bar{\lambda}}{cK_T}\Delta\nu \quad \text{or} \quad \text{Strain} = \varepsilon = -\frac{\bar{\lambda}}{cK_\varepsilon}\Delta\nu$$

where $\bar{\lambda}$ is the center wavelength of the scan; c is the speed of light; K_T and K_ε are the temperature and strain calibration constants, respectively; Δv = spectral shift.

Experimental Setup



Schematic diagram of the experimental setup for distributed strain measurements in a glass tube during electroless plating or metallic film dissolution

- Both the treated (sensitized and activated) section and a untreated fiber section as the control were inserted into a glass tube.
- The difference between the treated and untreated sections can provide insights into the strain changes solely caused by plating of metallic coatings (Ni or Fe), and the effects of temperature and water-induced strains would be compensated using the untreated control section.

Optical Fiber Preparation and Electroless Plating

- Optical fiber cleaning

Chemical	Conc.	Operation
Acetone	100%	Sonicate <5min
Dry in Air		

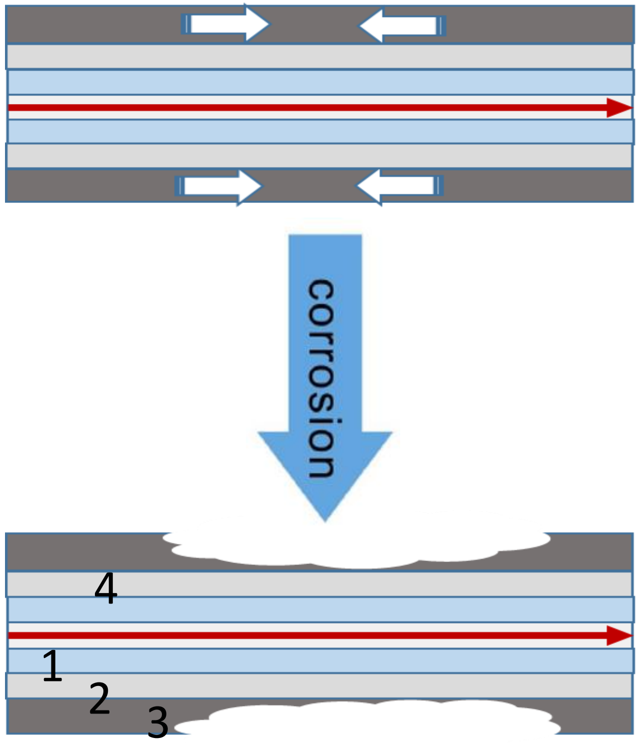
- Sensitization and Activation (Twice)

Chemical	Amount	Operation
$SnCl_2$	22.6g/L	30 seconds at 50 ^oC, rinse in DI water
HCl, conc.	10mL/L	
$PdCl_2$	0.795g/L	30 seconds at 50 ^oC, rinse in DI water
HCl, conc.	5mL/L	

- Electroless plating solutions and conditions

Electroless plating soln.	Ni (High pH)	Ni (Low pH)	Fe
Metal source	19 g/L $NiSO_4 \cdot 6H_2O$	19 g/L $NiSO_4 \cdot 6H_2O$	11 g/L $FeSO_4 \cdot 7H_2O$
Complexing agent	8 g/L $C_6H_5Na_3O_7 \cdot 2H_2O$	8 g/L $C_6H_5Na_3O_7 \cdot 2H_2O$	57 g/L $C_6H_5Na_3O_7 \cdot 2H_2O$
Reducing agent	15 g/L $NaH_2PO_2 \cdot H_2O$	15 g/L $NaH_2PO_2 \cdot H_2O$	3.0 g/L $NaBH_4$
pH stabilizer	6.5 g/L NH_4Cl	6.5 g/L NH_4Cl	10 g/L H_3BO_3
pH	10 @ 21.5 ^oC	5.8 @ 21.5 ^oC	10 @ 21.5 ^oC
Solution temperature	~50 ^oC	~50 ^oC	21.5 ^oC

Corrosion Sensing Principle based on Strain Changes on Optical Fibers



1: single-mode fiber core;

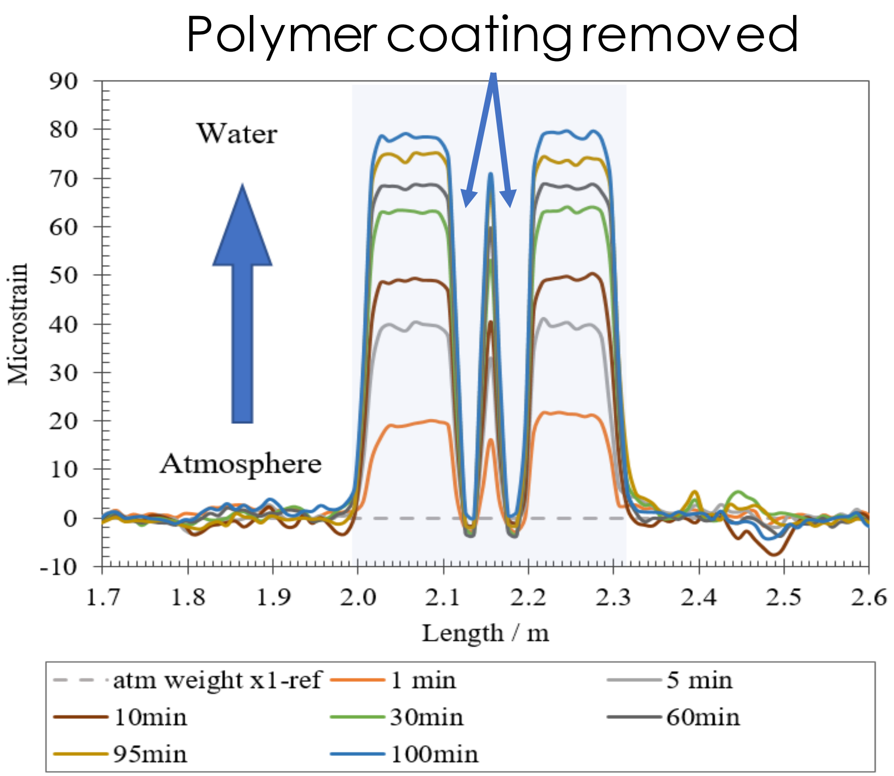
2: cladding;

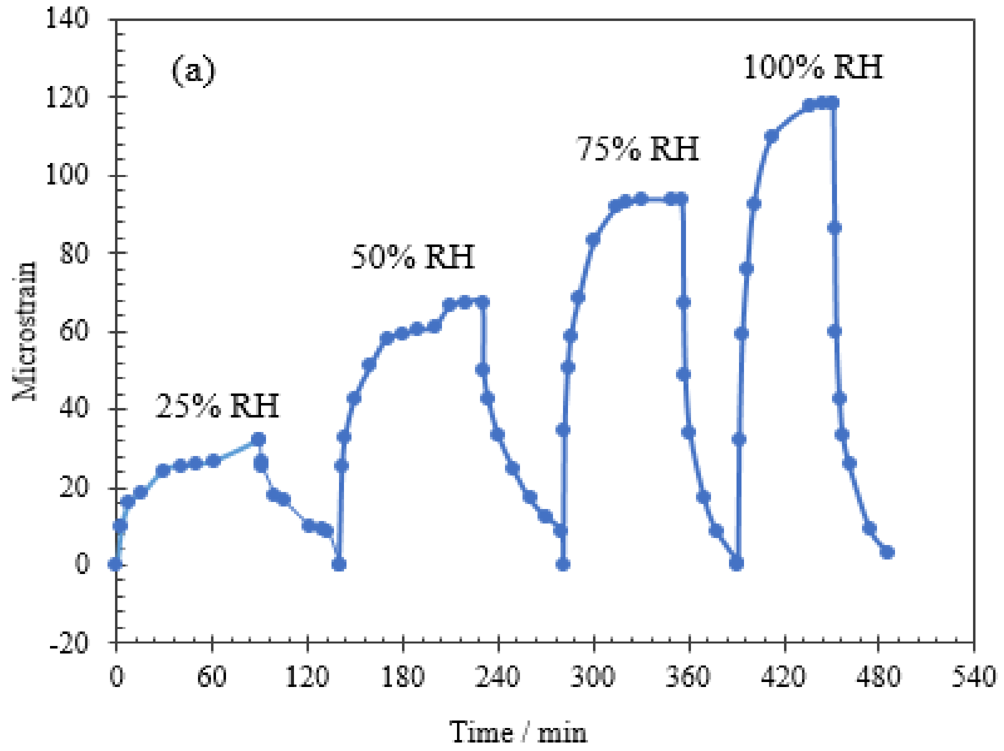
3: polymer jacket;

4: coated metallic film

- Inherent internal stress in the electrolessly plated metallic films can induce strains on the fiber.
- As the metallic film gets corroded, the internal stress will be released, causing changes in strains which can be measured using OBR.

Water and Humidity Sensors From Previous Work

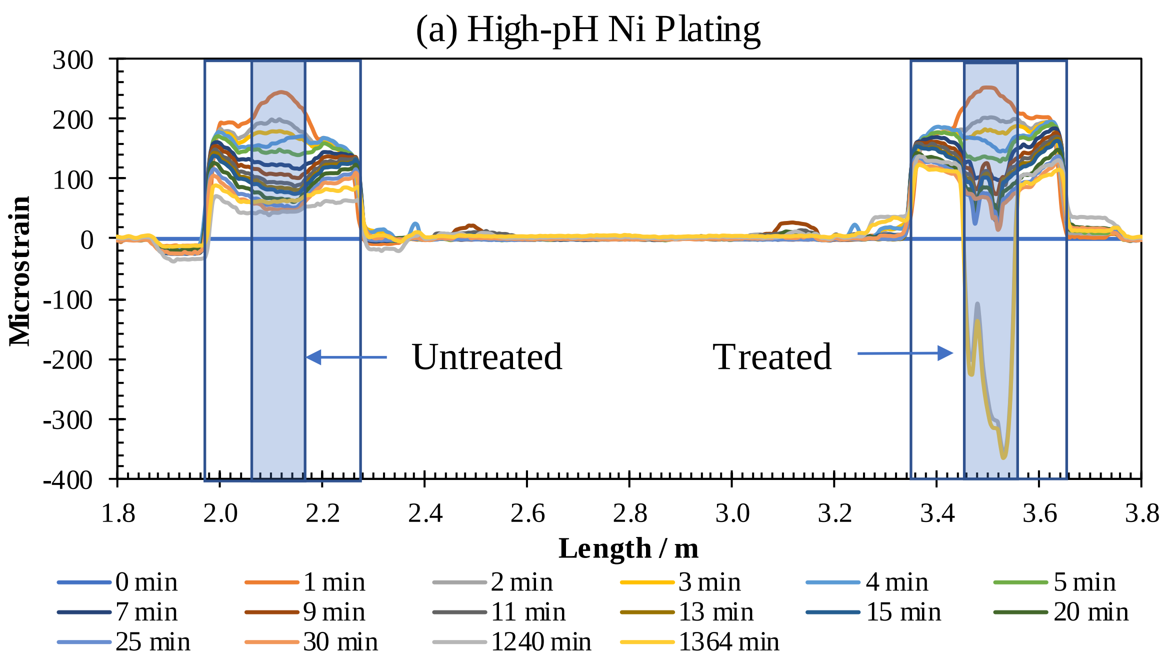


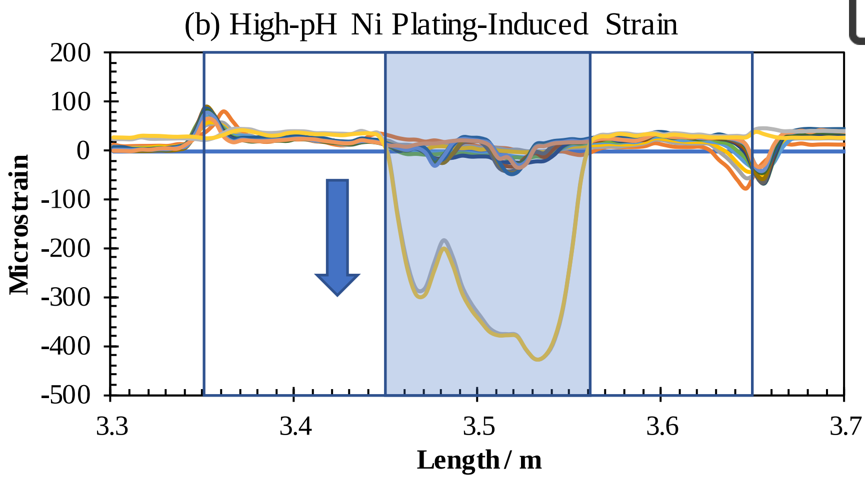


- The intrinsic hygroscopic polymer jacket coating of SMF-28Ultra serves as the water sensing layer due to expansion/swelling from water absorption.
- Reversible humidity sensing and linear correlation between humidity levels and strain along the fiber at room temperature.

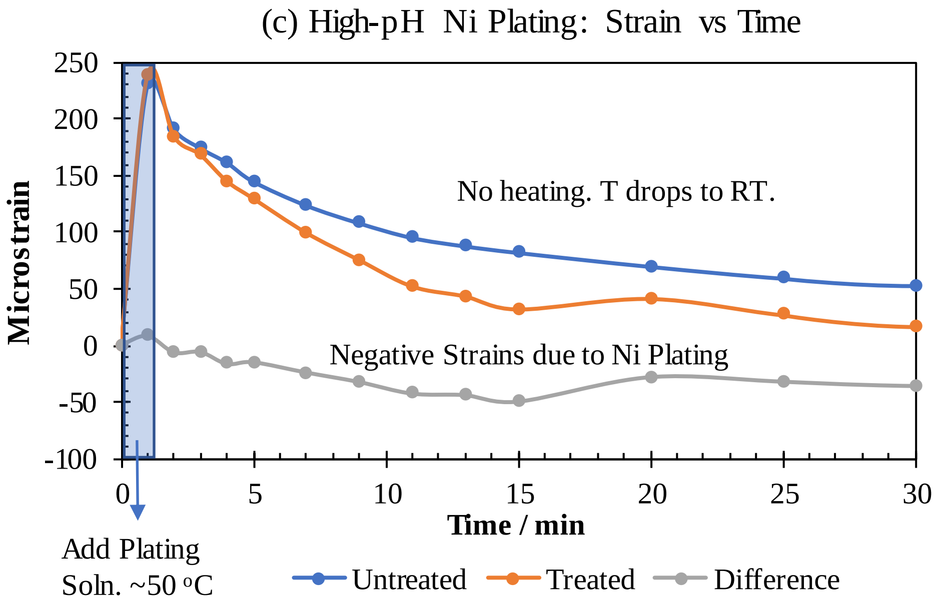
R F. Wright, et al. "Fully distributed optical fiber sensor for water and humidity monitoring," Proc. SPIE 11000, Fiber Optic Sensors and Applications XVI, 1100007 (14 May 2019)

High-pH Ni Plating Induced Negative Strains



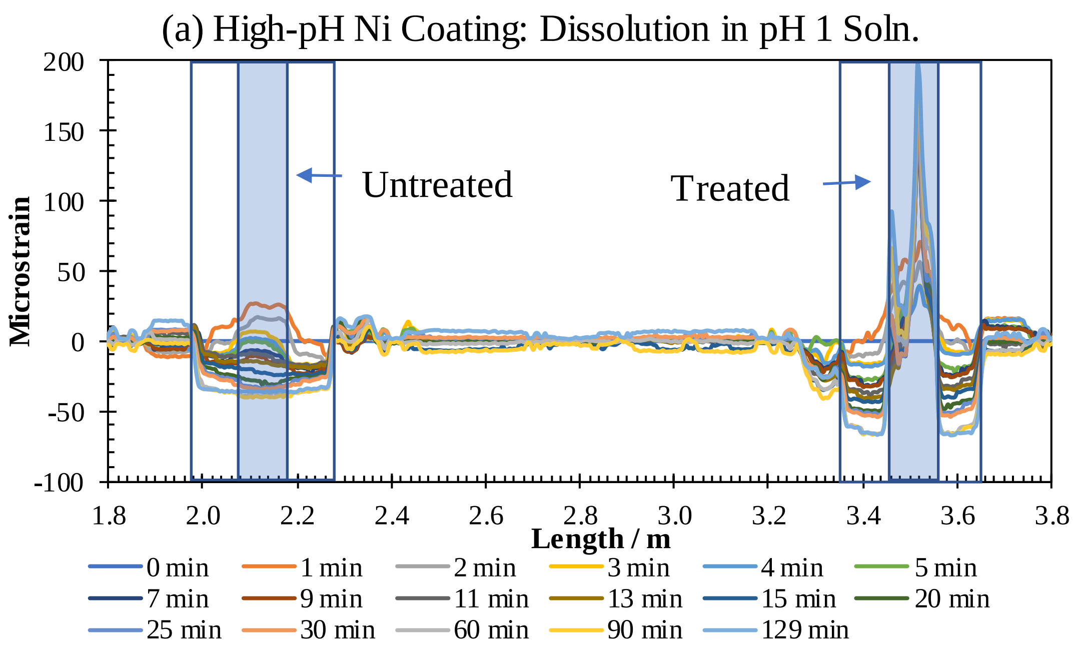


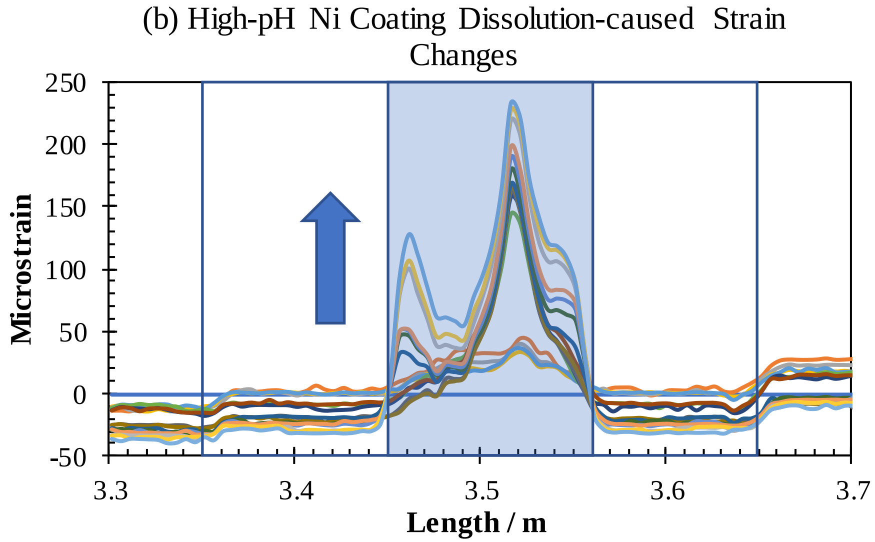
Treated subtracted by untreated



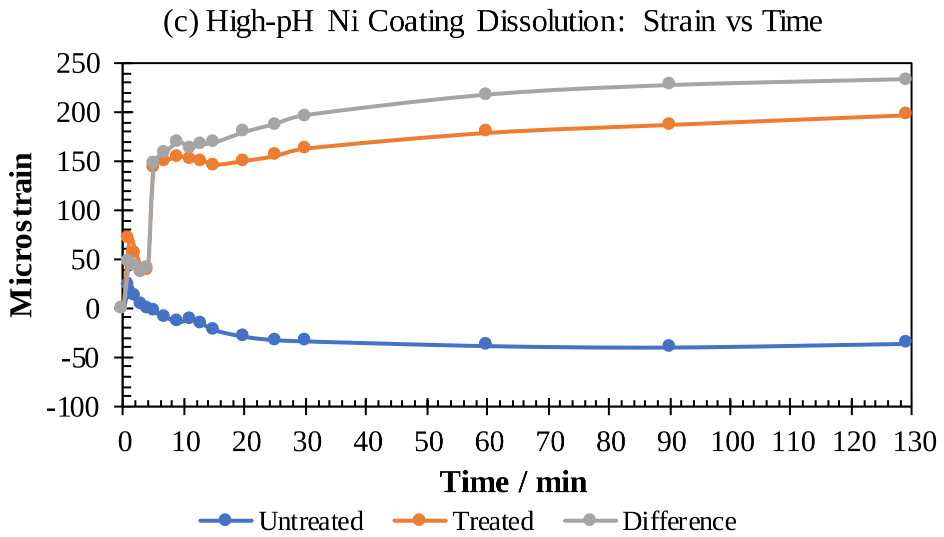
- Rectangles highlight the solution region inside the tube.
- Gray areas highlight the treated and untreated sections.
- **Untreated section**: strain increased due to ~50 °C Ni plating solution and water-induced swelling; then decreased as the solution cooled down (no heating).
- **Treated section**: strain decreased comparatively due to Ni plating. 30 min: -36 με; 22 hr: -430 με.

High-pH Ni Coating: Dissolution Induced Positive Strains



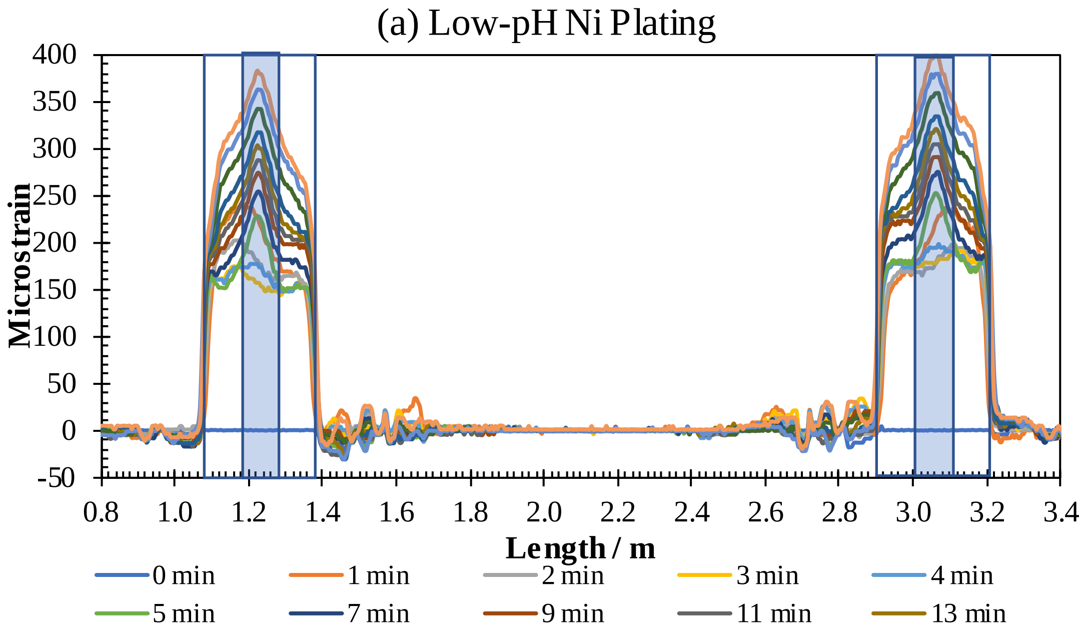


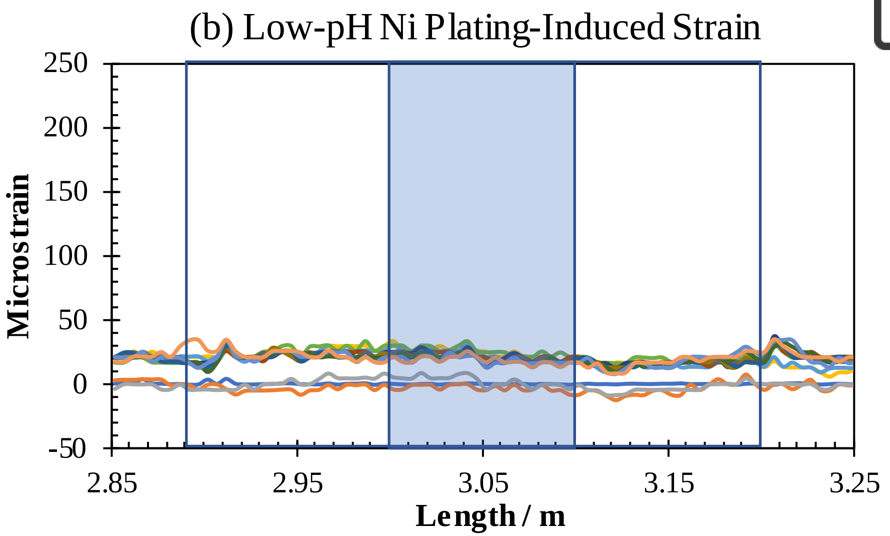
Treated subtracted by Untreated



- After plating, high-pH Ni coating was exposed to pH 1 HCl soln.
- **Untreated section**: at room temperature (RT), strain showed a minimal decrease to -36 με.
- **Treated section**: strain increased up to 233 με due to Ni dissolution. Two preferable dissolution locations, corresponding to Ni deposition strains.

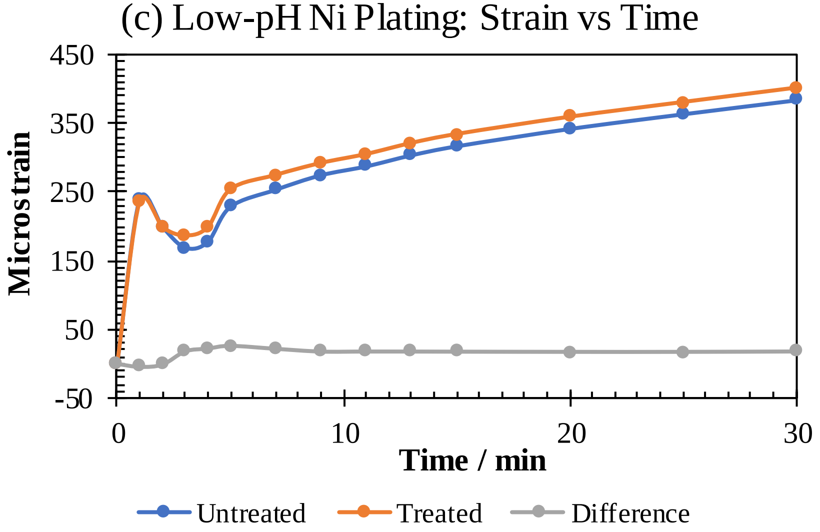
Low-pH Ni Plating Induced Minimal Strains



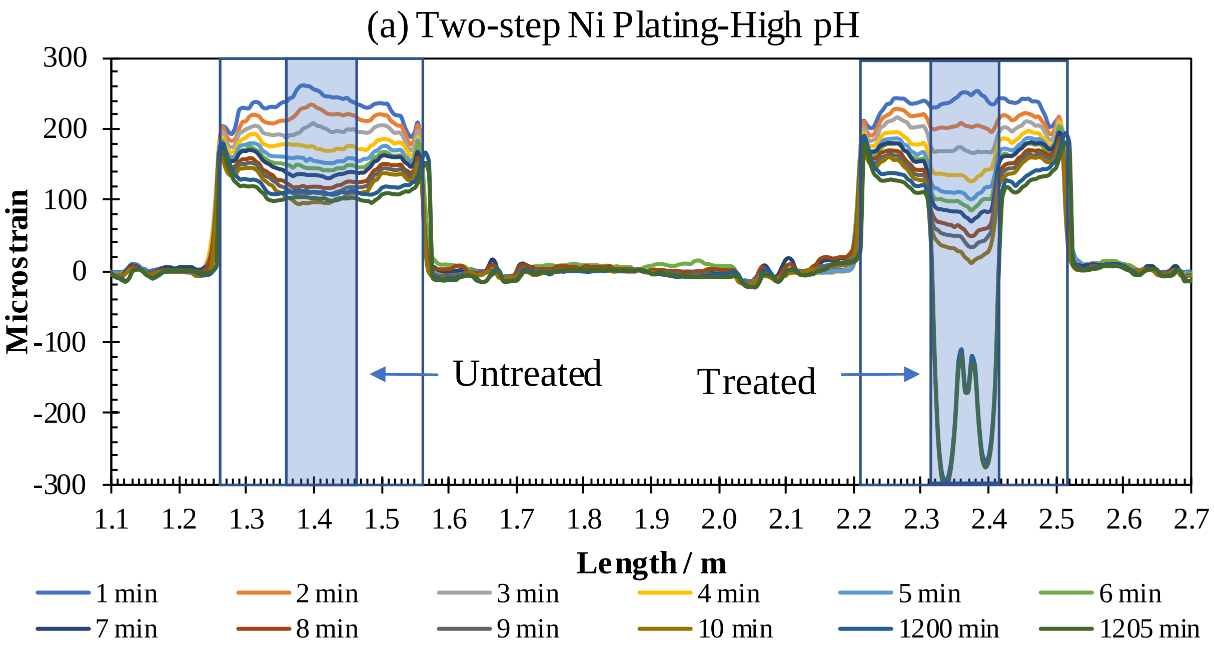


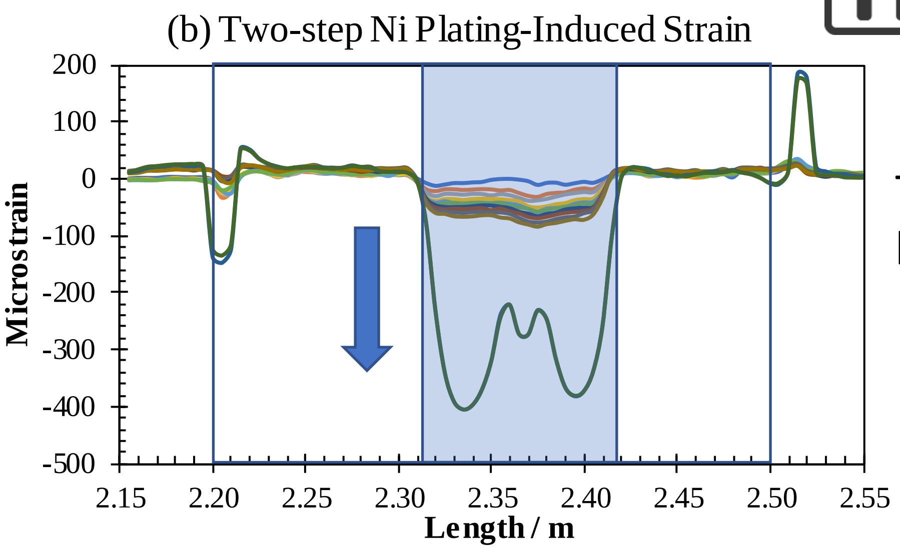
Treated subtracted by Untreated

- **Untreated section**: strain increased due to ~50 ^{o}C Ni plating solution and water-induced swelling.
- **Treated section**: strain increased similarly to the untreated section, leading to minimal strains due to Ni plating.



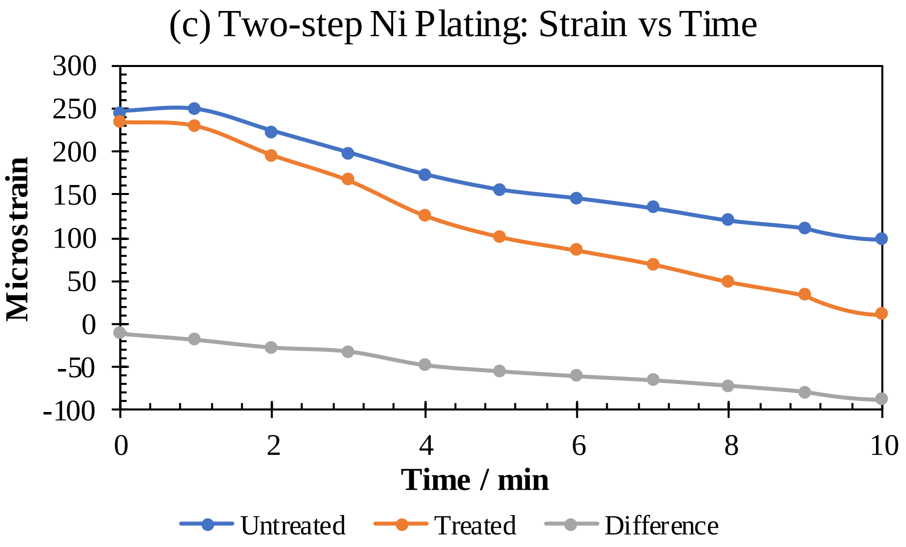
Two-Step Ni Plating: High-pH Ni Plating Induced Negative Strains



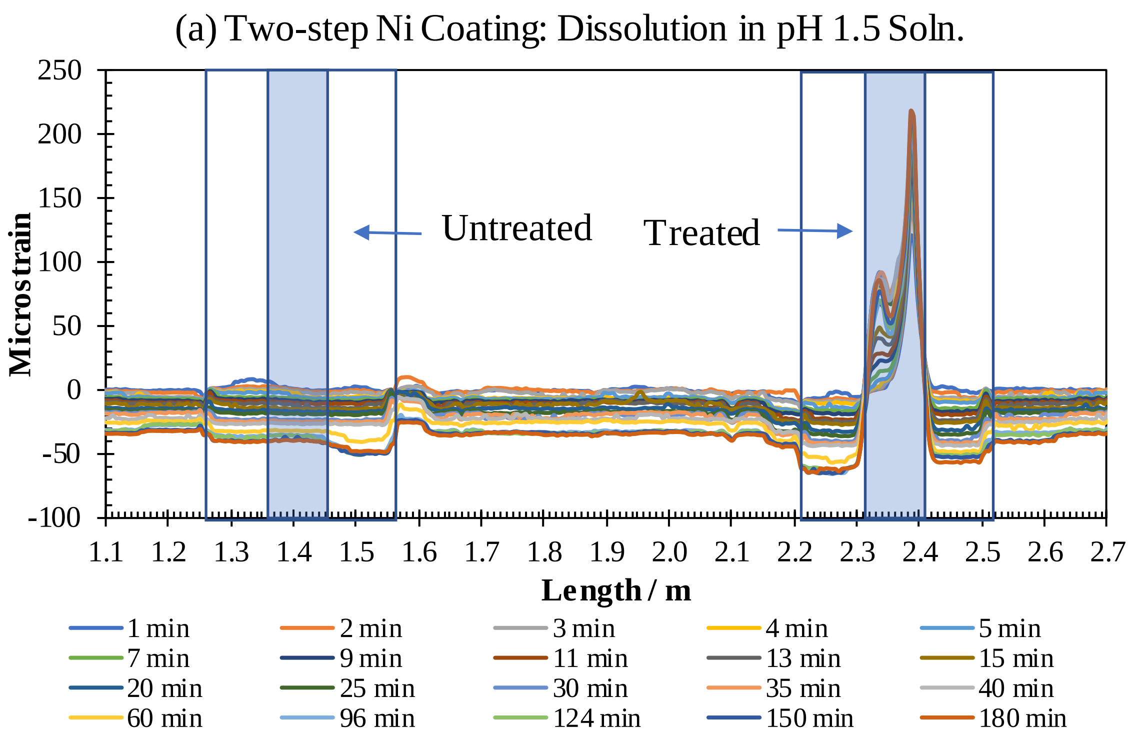


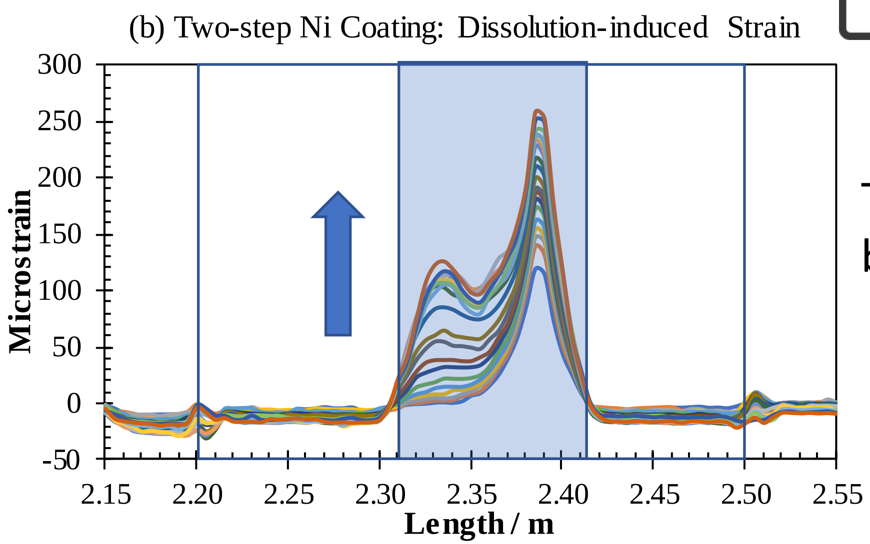
Treated subtracted by Untreated

- Two-step Ni plating: Low-pH plating solution for 6 min to deposit the initial layer; then high-pH plating solution with a faster plating rate.
- **Untreated section**: strain increased due to ~50 °C Ni plating solution and water-induced swelling; then decreased as the solution cooled down (no heating).
- **Treated section**: strain decreased comparatively due to high-pH Ni plating. 10 min: -88 µε; 20 hr: -407 µε.

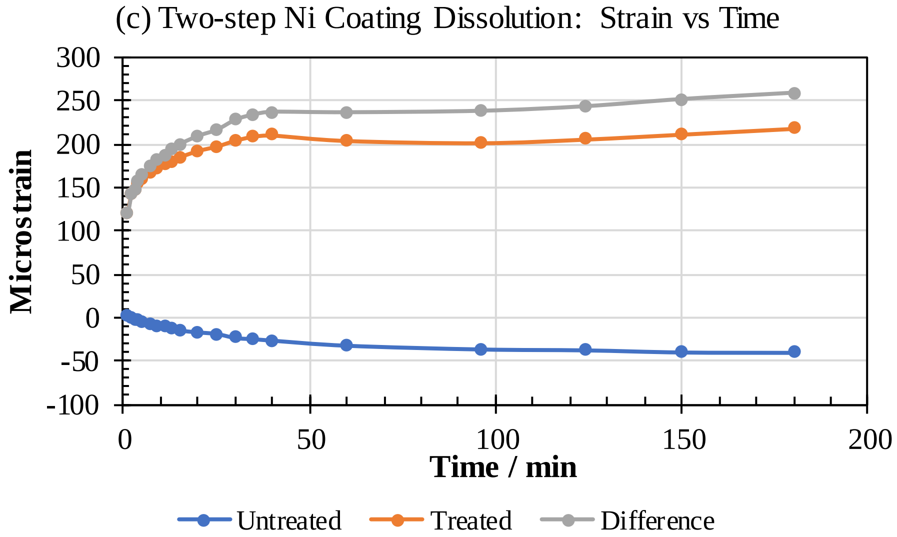


Two-Step Ni Coating: Dissolution Induced Positive Strains



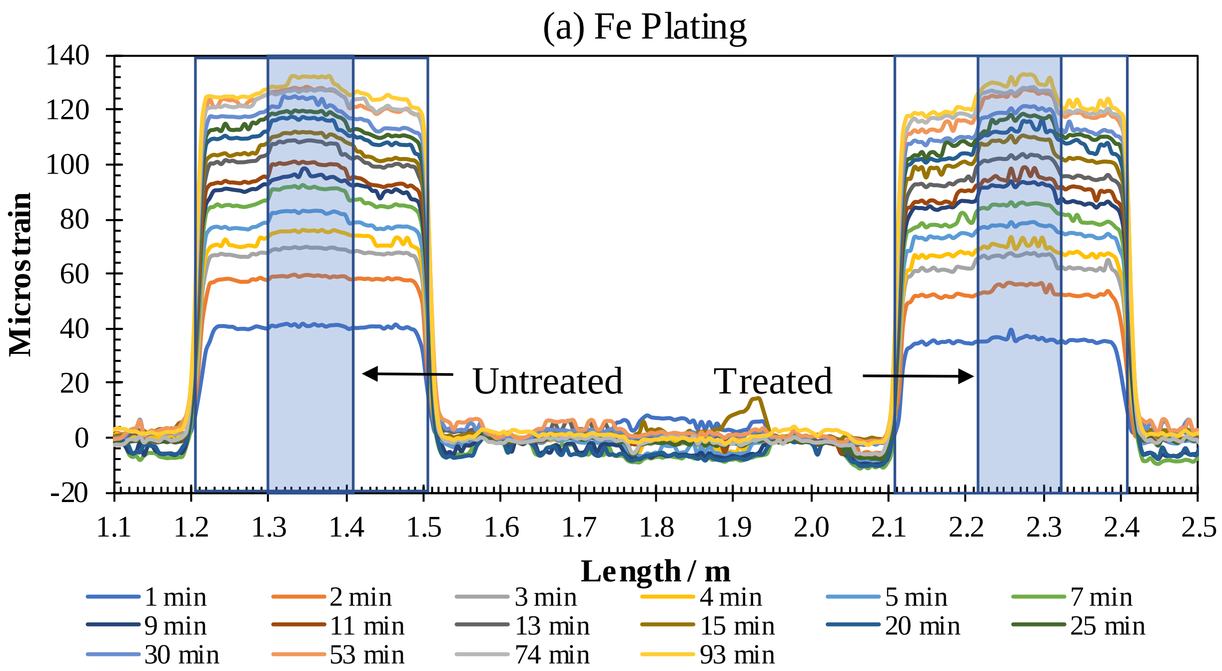


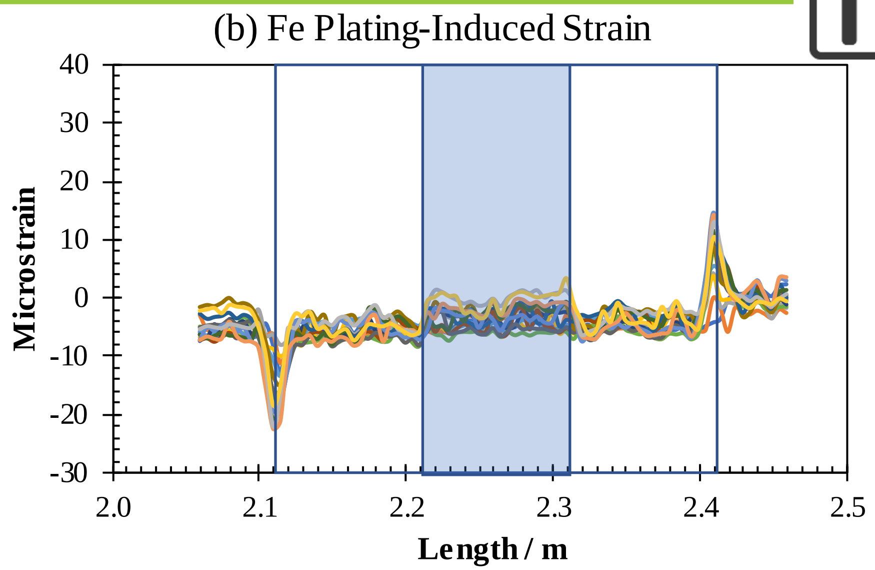
Treated subtracted by Untreated



- After plating, two-step Ni coating was exposed to pH 1.5 HCl soln.
- **Untreated section**: at RT, strain showed minimal changes.
- **Treated section**: strain increased comparatively up to ~260 με due to Ni dissolution. Two preferable dissolution locations, corresponding to Ni deposition strains.

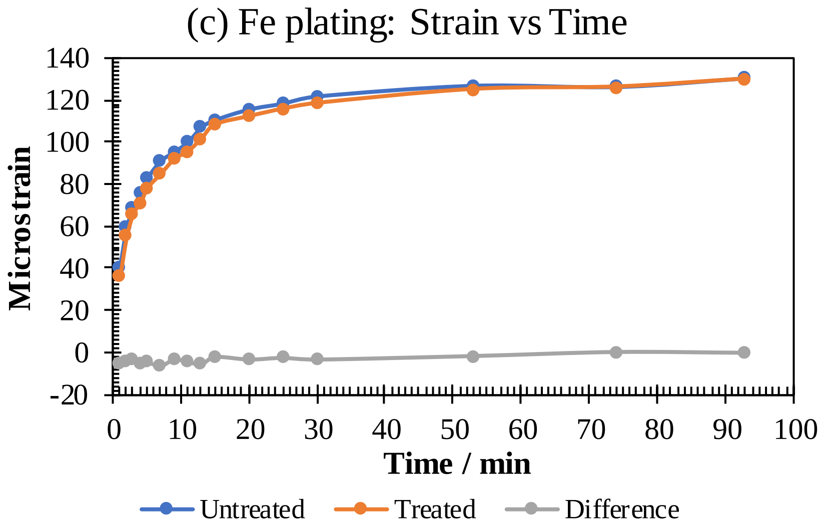
Fe Plating Induced Negligible Strains





Treated subtracted by Untreated

- **Untreated section**: at RT, strain increased due to water-induced swelling.
- **Treated section**: strain increased similarly to the untreated section, leading to minimal strains (near-zero) due to Fe plating.



Conclusions

- A distributed optical fiber corrosion sensor was demonstrated based on strain changes on the optical fiber, interrogated using an OBR.
- Electroless plating leads to inherent internal stress in the metallic coating, and induces strains on the fiber. As the metallic film gets corroded, the internal stress will be released, causing changes in strains, which can be used as an indicator for dissolution/mass loss.
- The difference between the treated and untreated sections can provide insights into the strain changes solely caused by plating of metallic coatings (Ni or Fe), and the effects of temperature and water-induced strains would be compensated using the untreated control section.
- High-pH Ni plating had a faster deposition rate and induced negative strains, and the dissolution induced positive strains in the corresponding coating locations.
- Low-pH Ni plating and Fe plating had a relative slow and smooth coating, which induced minimal strains.
- Two-step Ni plating includes low-pH plating to deposit an initial layer and then high-pH plating with a faster deposition rate. The high-pH Ni plating induced negative strains.

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