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From Underground to the Forefront of Innovation and Sustainability

Innovative Fiber Optic Sensors for Pipeline Corrosion Monitoring

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Outline

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- *Operational Principles and Sensor Design*
  - *Corrosion process of iron particles*
  - *Review of Existing Technologies for corrosion detection*
  - *Sensor structure and sensing principle*
  - *Coating composition and characteristics*
- *Experiments and Discussion*
  - *Calibration of the coated sensor*
  - *Accelerated corrosion test for the coated LPFG sensor*
  - *Accelerated corrosion test for steel rebar using proposed sensors*
- *Concluding comments & future work*

Introduction

U.S. has the largest pipeline network around the world, of 793,285 km, including petroleum products of 244,620 km and natural gas of 548,665 km.

No. 1 reason for costly maintenances of pipeline infrastructure.

Operational Principles

❑ *Corrosion process of iron particles*

The corrosion of iorn is an electrochemical process which involves exchanges of electrons. With the presence of water and oxygen, the iron is oxidised to be ferrous ions and is prone to be migrated with the catholic sites:

$$2Fe^{2+} + 4OH^{-} \rightarrow 2Fe(OH)_2$$

Further oxidation of Fe^{2+} to Fe^{3+} also exists with sufficient water and oxygen:

$$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3$$

The hydrated ferric oxide owns a color of orange to red-brown and it is the largest components of the rust products after corrosion process of iron based products.

Operational Principles

❑ *Existing technologies for corrosion assessment*

➢**Material sacrificial:** Directly measures the corrosion-induced loss of materials by monitoring.

✓ valuable to pin-point corrosion

○**Not real-time and remote**
○**Hard for large structures & oversea structures**
○**Destructive for direct member mass loss measurement**

➢**Physical:** Quantify the corrosion-induced degradation of structures by measuring various physical quantities such as strain, guided wave, ultrasonic, and acoustic waves

✓Suitable for the monitoring of structural health conditions that could result from corrosion or non-corrosion related factors

○**Hard for large structures**

➢**Electrochemical:** Quantify the corrosion-related electrochemical process by measuring either the electrical fields/potentials at the steel surface or the corrosion environmental factors such as chloride content and pH of pore fluids.

✓Most commonly used approach

✓Useful to understand the corrosion mechanism and related remediation methods

○**Not real-time remote**
○**Hard for large structures**

With their distinctly different advantages and disadvantages, current technologies are yet to be further advanced to develop a real-time remote monitoring system for corrosion assessment of large-scale structures.

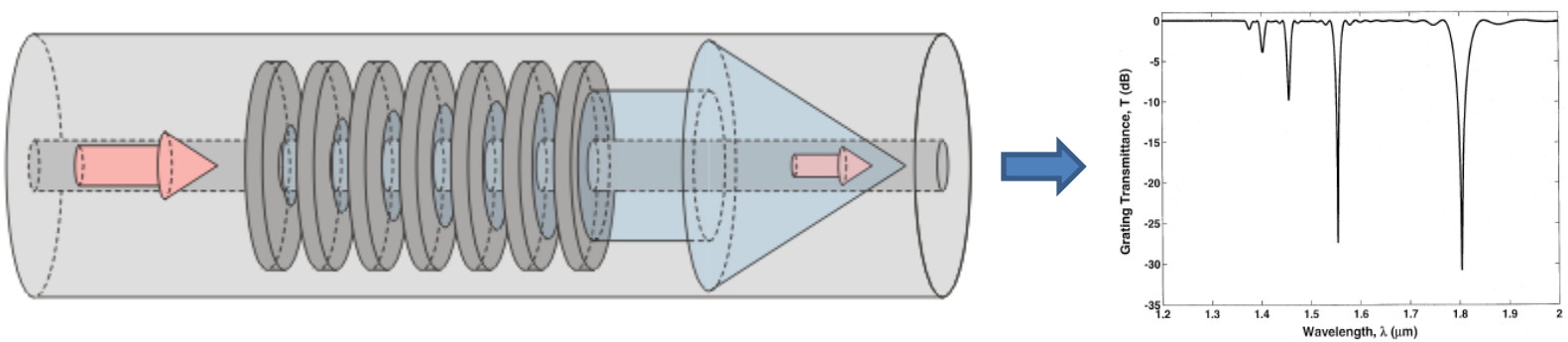
Sensor Design

❑ *Operational principles of LPFG sensors*

- A **long-period fiber grating** couples light from a guided mode into forward propagating cladding modes where it is lost due to absorption and scattering. It is an optical fiber structure with the properties periodically varying along the fiber, such that the conditions for the interaction of several copropagating modes are satisfied. The period of such a structure is of the order of a fraction of a millimeter. The transmission spectrum has dips at the wavelengths corresponding to resonances with various cladding modes (in a single-mode fiber).

$$\lambda_{re,m} = (n_{eff,co} - n_{eff,cl,m})\Lambda$$

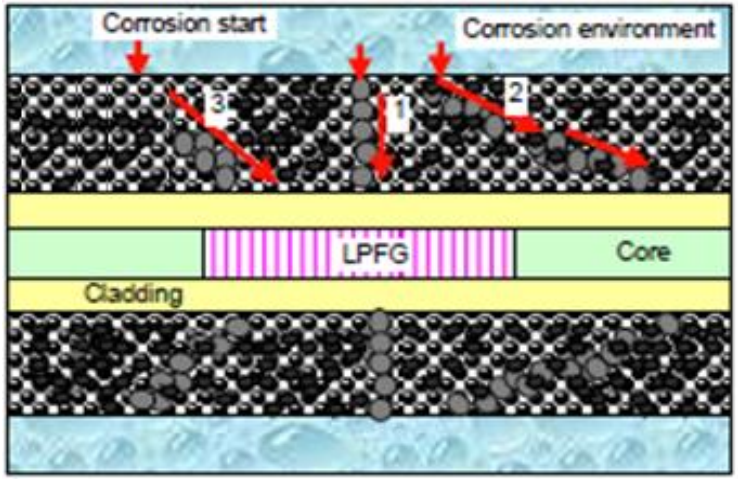
Highly related to the coating material and thickness on the grating surface

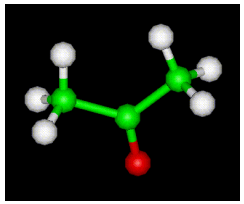


By coating a thin layer on the out-surface of the grating, it is possible for the LPFG sensor to pick up the corrosion information of the monitored steel members.

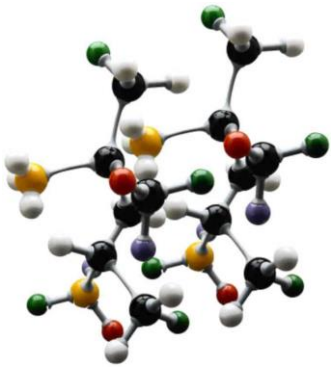
Sensor Design

❑ *Sensor structure & coating compositions*

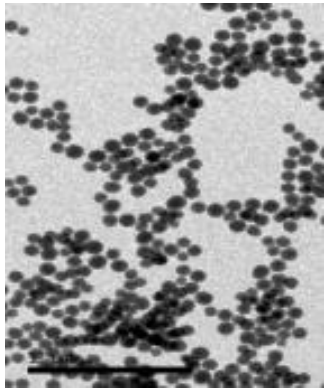




Acetone



Polyurethane



Nano silica particles
Maximum dia. < 7nm

Dipping solution

Nano iron particles
Maximum dia. < 100nm

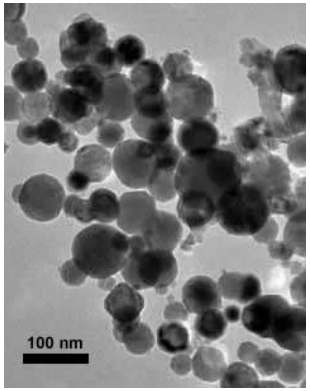


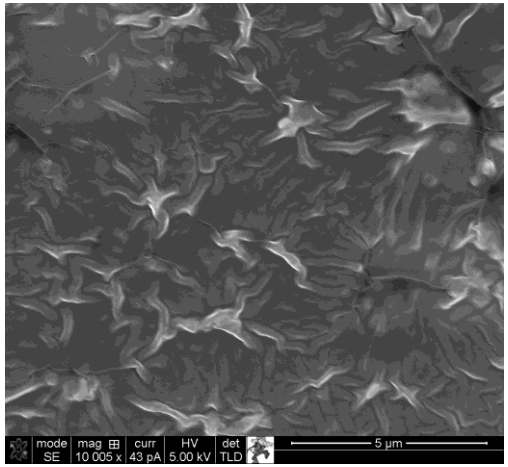
Table 1 Chemical composition of nano iron particles

Element	Al	Ti	Mo	Ca	Ni	Sn	Cr	Cu	Mn	Si	Fe
Wt.%	0.02	0.0013	0.0035	0.0035	0.002	0.002	0.0038	0.03	0.0075	0.0025	99

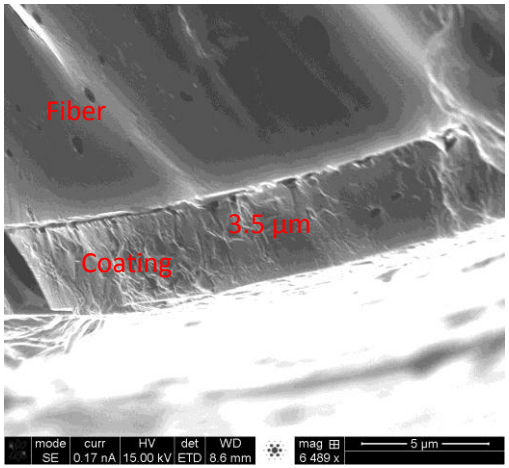
Sensor Design

❑ *Coating characteristics*

Composition: 1: 2:10:10:400 (Iron: silica: isocyanate: resin: acetone)



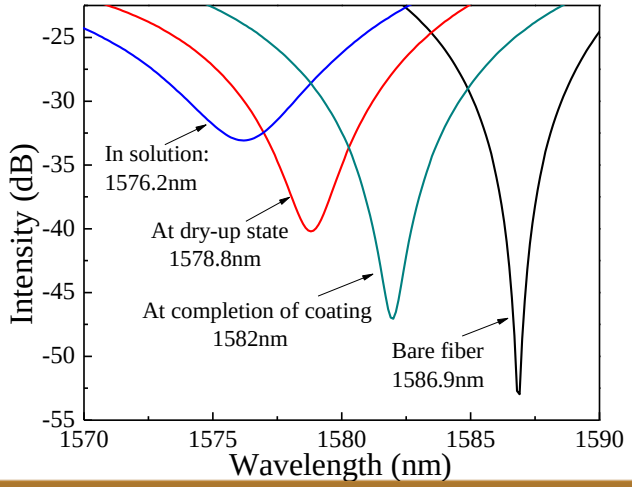
Surface condition



Cross-section (thickness of the coating: around 3.5 µm)

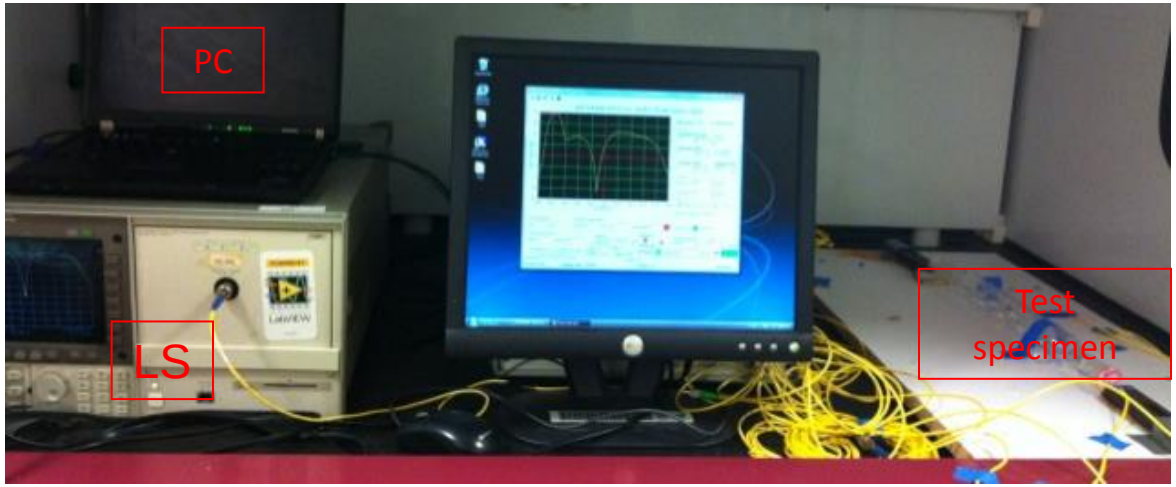
With nano particles

LPFG spectrum change during the coating process

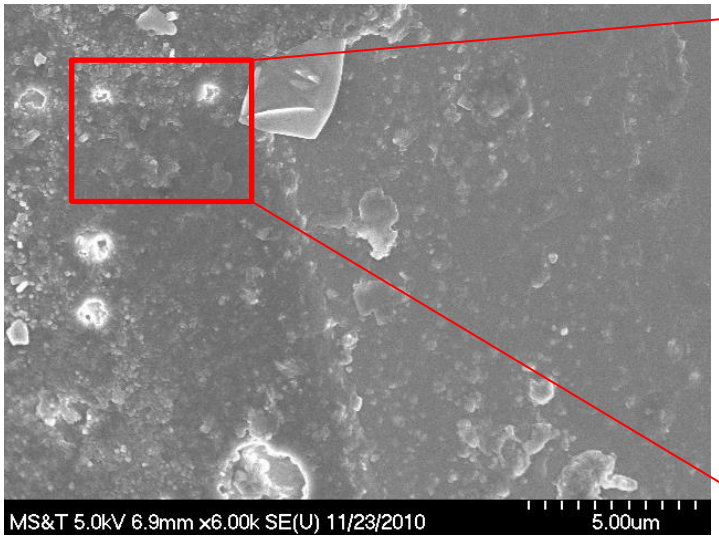


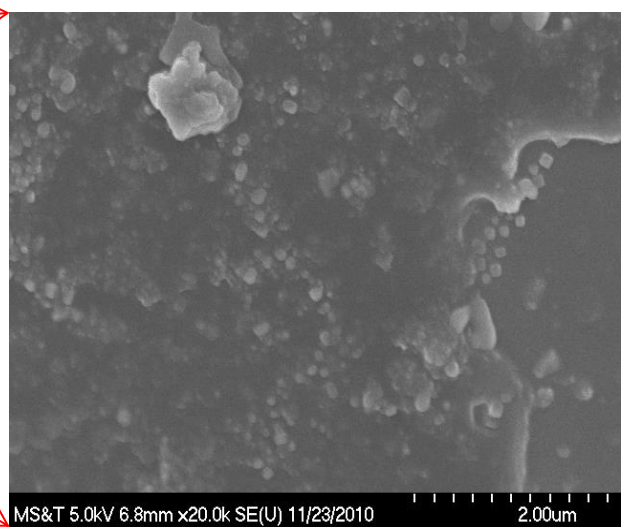
Experiments and Discussions

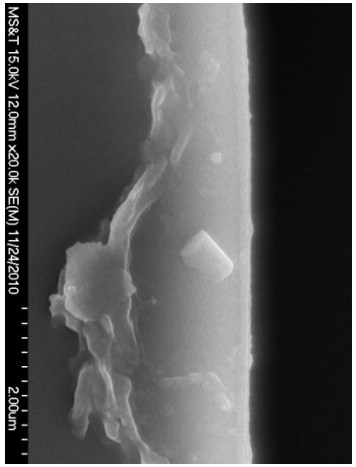
- *Calibration test for the nano iron/silica particle polyurethane coated LPFG sensor*



Test setup



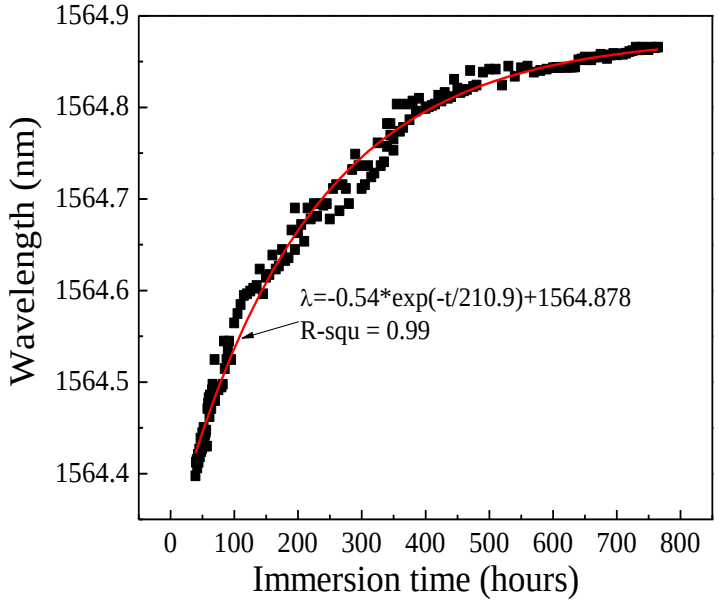




Surface condition after corrosion test for 30 days

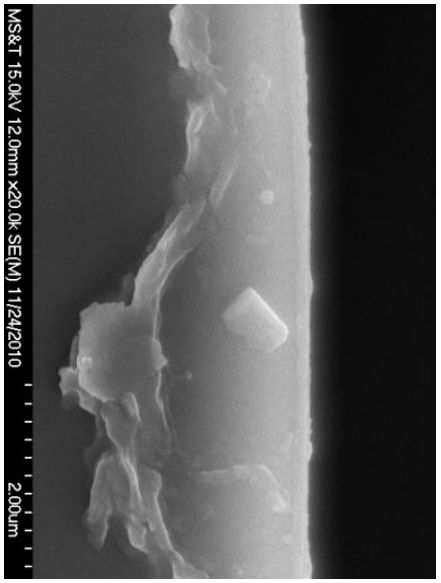
Experiments and Discussions

- *Calibration test for the nano iron/silica particle polyurethane coated LPFG sensor*



Resonant wavelength change of coated LPFG versus immersing time

The increase in resonant wavelength at the end of corrosion testing, approximately 0.45 nm, corresponds to approximately 9% of the total wavelength shift.



Cross-section

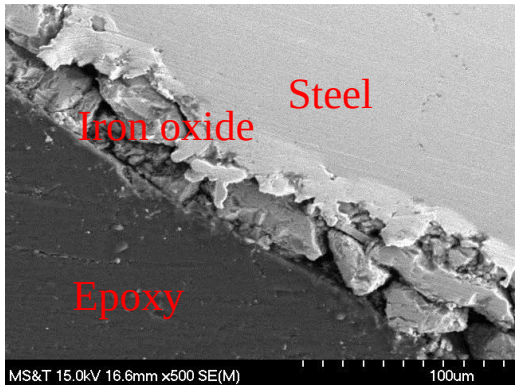
After the coating has been immersed in the 3.5% NaCl solution for one month, a thickness loss of 0.24 μm or a 9.6% thickness reduction compared to the 2.5 μm initial coating thickness.

Experiments and Discussions

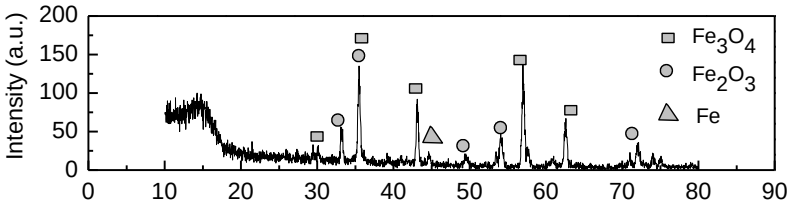
- *Corrosion monitoring of steel rebar by the proposed sensors: rebar preparation*

Table 2 Chemical composition of test steel rebar

Element	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	V	Sn	Fe
Wt.%	0.383	0.184	1.000	0.115	0.064	0.103	0.069	0.198	0.373	0.022	0.028	97.40



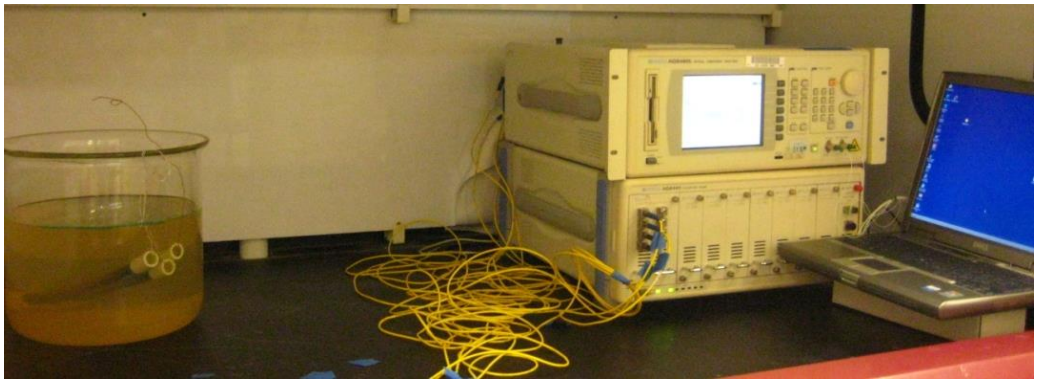
Cross section of steel bar before corrosion test



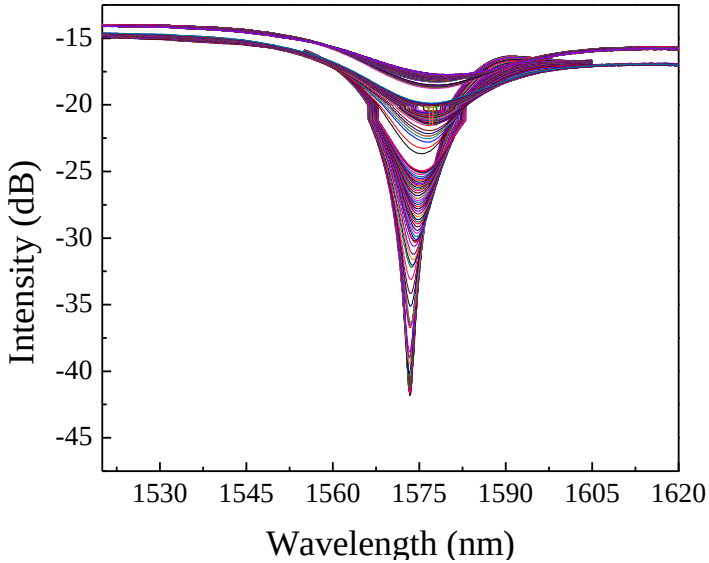
EDS analyses of the steel rebar samples

Experiments and Discussions

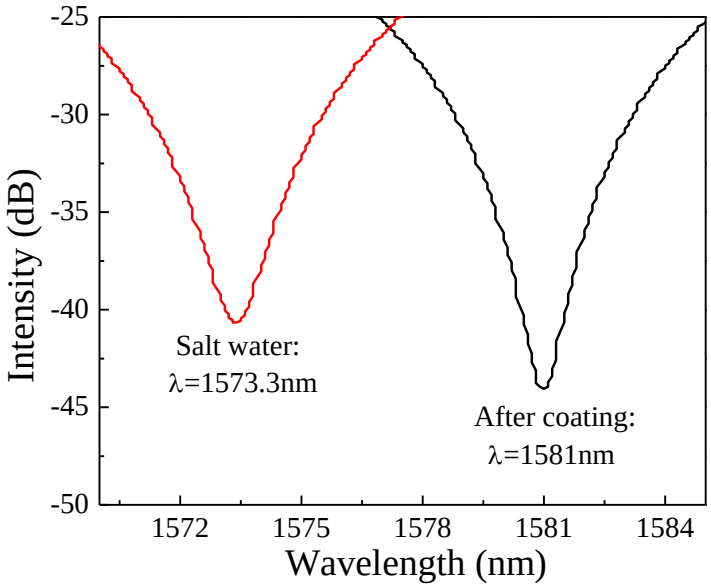
- *Corrosion monitoring of steel rebar by the proposed sensors: test setup & LPFG results*



Corrosion test setup



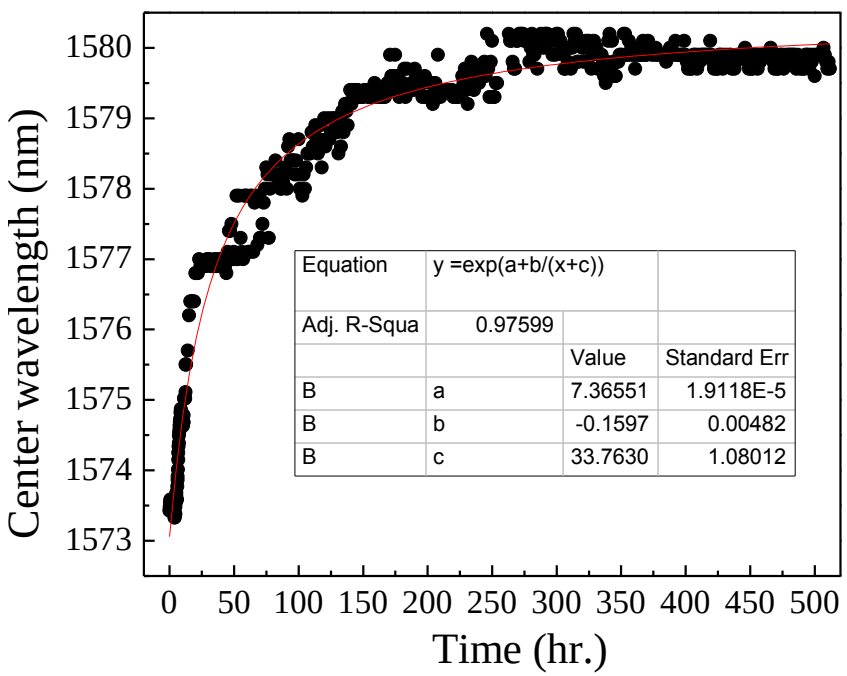
Coated LPFG spectrum change for 1 month corrosion test



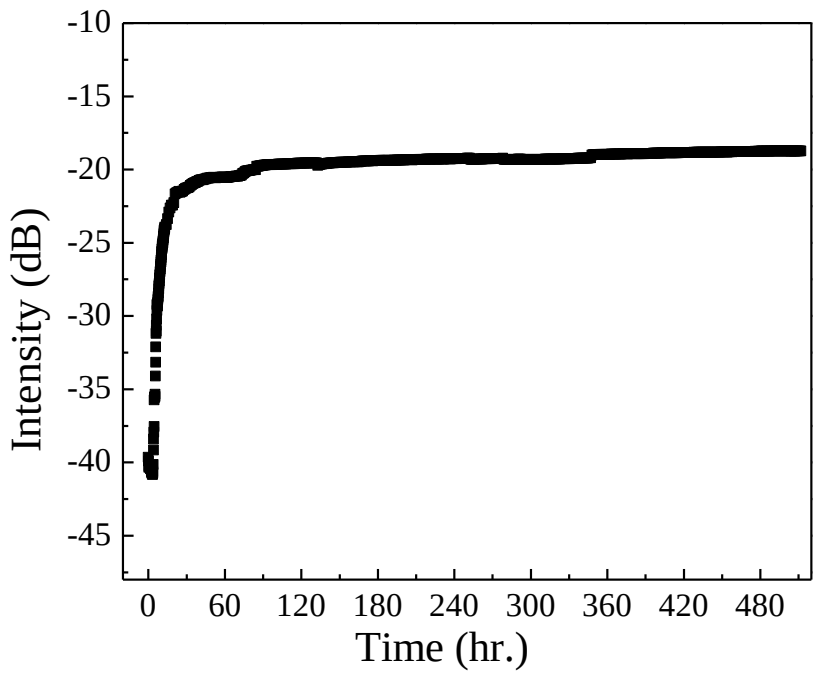
Spectrum change before and after placing of the coated LPFG in 3.5% salt water

Experiments and Discussions

- *Corrosion monitoring of steel rebar by the proposed sensors: LPFG monitored results*



Wavelength change with immersing time



Intensity change with immersing time

Conclusion & Future work

(a) A novel long period fiber grating based corrosion sensor is proposed for a long-term deterioration assessment of pipeline.

(b) The proposed corrosion sensor is manufactured by coating a thin layer of nano iron/silica particles dispersed polyurethane around the surface of an optic fiber inscribed with long period fiber gratings (LPFG).

(c) The coated LPFG sensor was calibrated in 3.5% salt solution. It was observed that some nano particles were corroded and the corroded particles left behind with local cavities in the coating, causing the shift of resonant wavelength of the LPFG.

(d) Another accelerated corrosion tests were operated for steel rebar by applying the proposed coated LPFG in 3.5% salt solution. Test results show interesting results and approves the needs for future investigations.

(e) With the experiences from the tests, it is possible to obtain a good application opportunity for corrosion monitoring using this technique for undersea steel oil pipeline, oversea platform, and steel bridges.

(f) For a better understanding before the field application, future investigation of this technique is needed though. I propose to have a series of intensive validation tests considering various corrosion environments including salt chamber, atmospheric corrosion, and others. More specimens used together with the monitored specimens to calibrate the mass loss directly instead of correlated from electrochemical tests or may be combined with electrochemical tests.

ACKNOWLEDGEMENTS

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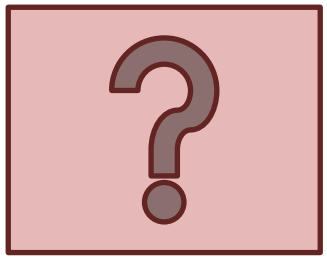
Thank you!

Question?