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Fiber Optic Sensor Based Corrosion Assessment in Reinforced Concrete Members

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INSPIRE

INSPECTING AND PRESERVING INFRASTRUCTURE THROUGH ROBOTIC EXPLORATION

FIBER OPTIC SENSOR BASED CORROSION ASSESSMENT IN REINFORCED CONCRETE MEMBERS

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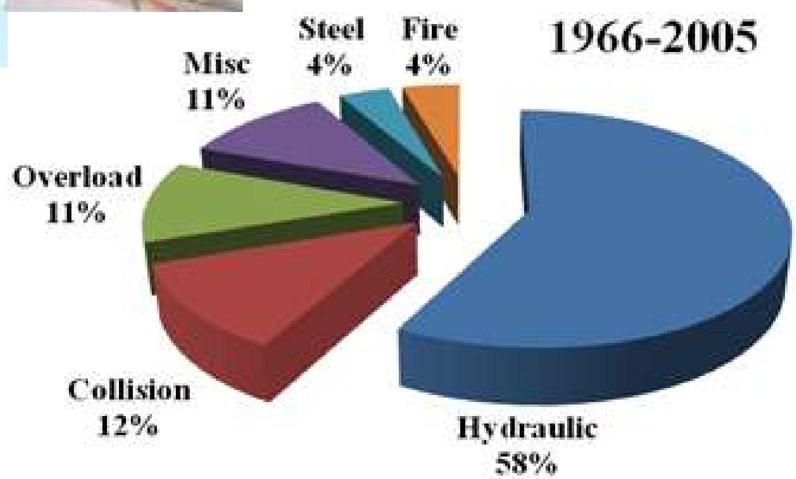
Outline of This Presentation

- Introduction
- Lab-on-sensor Concept and Theory
- Long Period Fiber Gratings (LPFG): Design and Fabrication
- LPFG for Strain, Temperature and Refractive Index Sensing
- Fe-C Coated LPFG for Corrosion Induced Mass Loss Measurement
- Probability of Detection in Corrosion
- Concluding Remarks

Introduction to Corrosion Problem

- **Significance**
  - **Corrosion cost was in the order of trillion dollars in 2012**

Schematic view of various structural behaviors



Causes of over 1500 bridge collapses

Introduction to Corrosion Factors

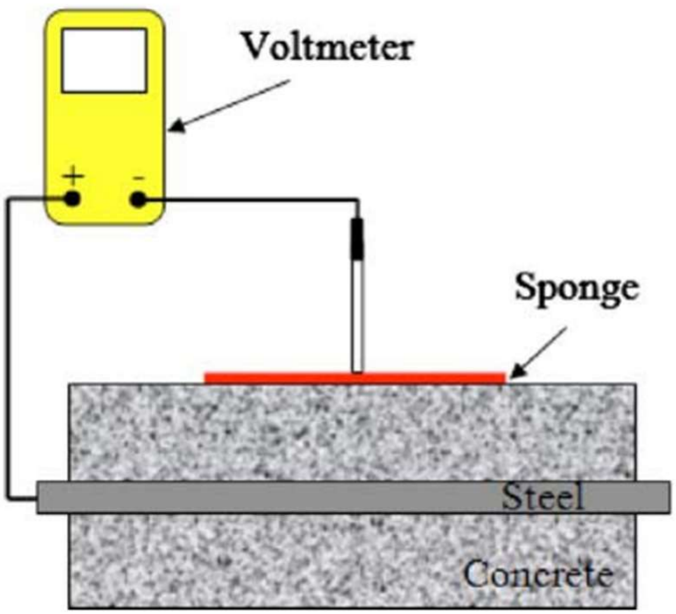
- **Metal Affecting Factors**
  - Composition, presence of impurities, phases and constituents
  - Crystalline structure, constituent phases, lattice defects, surface finishing grain boundary precipitates and mechanical stresses
- **Environment Affecting Factors**
  - Conductivity
  - pH
  - Oxygen content
  - Etc.
- **Metal/Environment Affecting Factors**
  - Temperature
  - Condensation
  - Corrosion products and deposits
  - Etc.

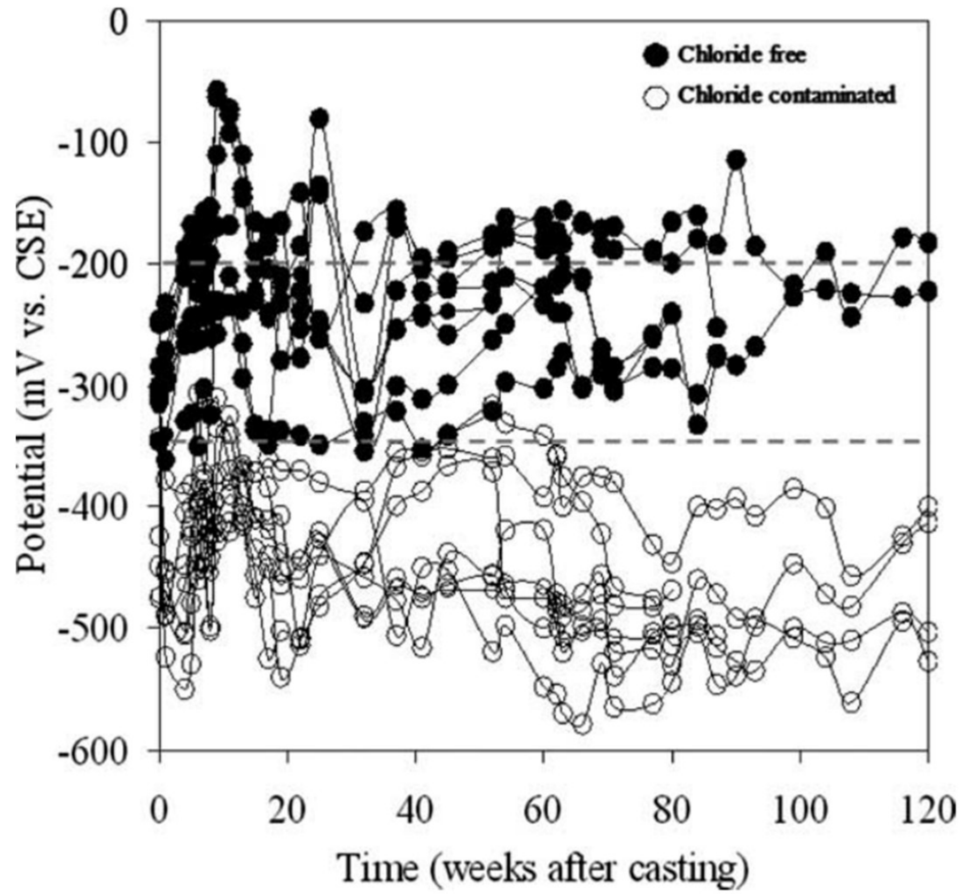
Introduction to Corrosion Monitoring

- **Monitoring Methods in Metal Pipeline Application**
  - **Electrochemical techniques**
    - ✓ ***Half-cell potential***
    - ✓ ***Linear polarization resistance (LPR)***
    - ✓ ***Electrochemical impedance spectroscopy (EIS)***
    - ✓ ***Etc.***
  - **Physical and chemical**
    - ✓ ***Gravimetric techniques***
    - ✓ ***Electrical resistance technique***
    - ✓ ***Radioactive tracer method***
    - ✓ ***Acoustic emission***
    - ✓ ***Hydrogen flux***
    - ✓ ***Etc.***

Introduction to Corrosion Monitoring

- **Half-cell Potential Test on Rebar in Concrete Beam**

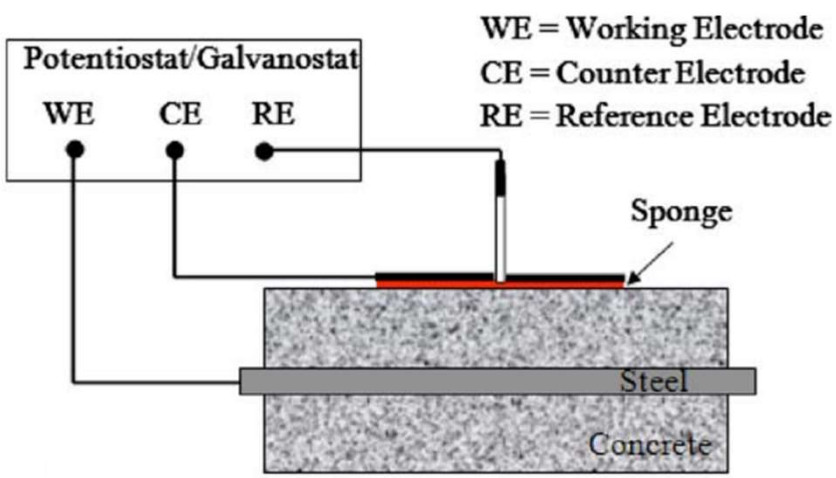


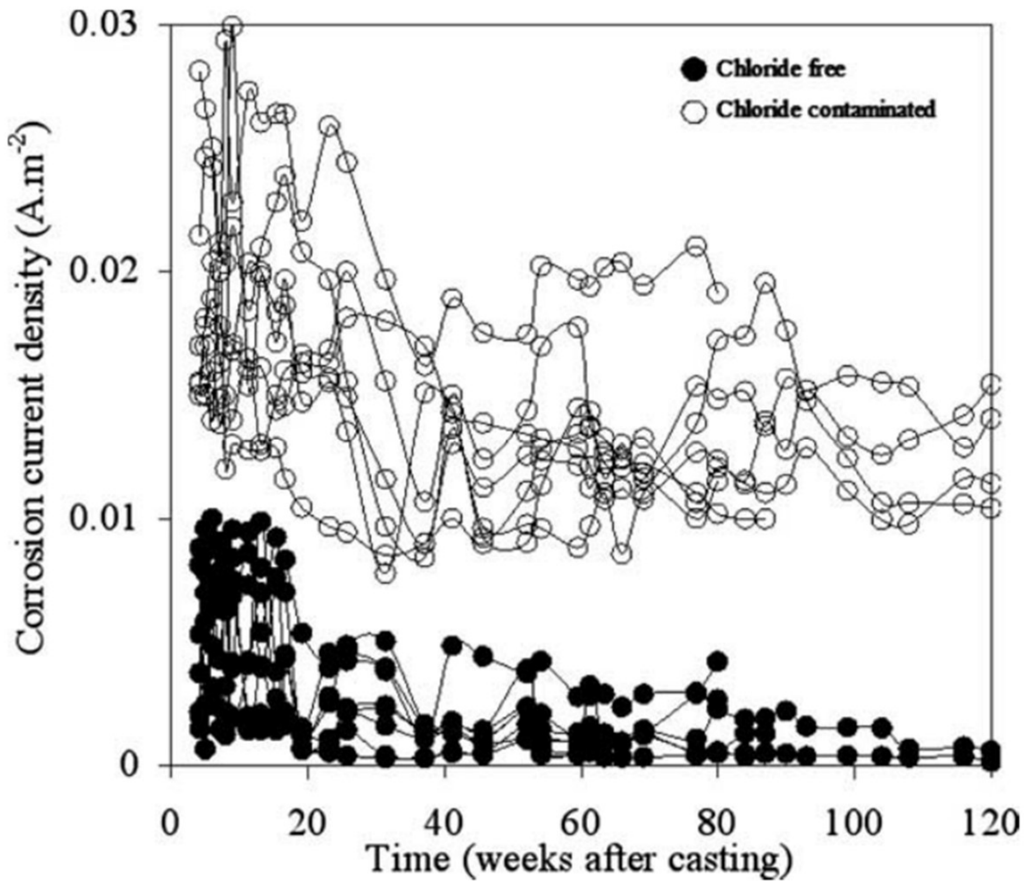


A. Poursaee. "Corrosion Measurement Techniques in Steel Reinforced Concrete," Journal of ASTM International 8(5): Paper ID JAI103283, May 2011.

Introduction to Corrosion Monitoring

- **Potentiostatic Linear Polarization Resistance Test on Rebar in Concrete Beam**





A. Poursaee. "Corrosion Measurement Techniques in Steel Reinforced Concrete," Journal of ASTM International 8(5): Paper ID JAI103283, May 2011.

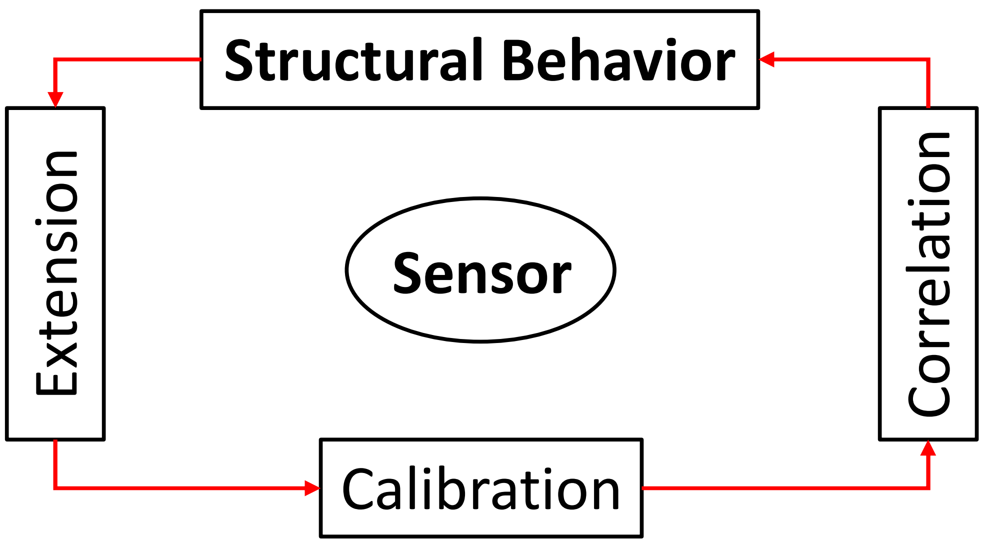
Lab-on-sensor Concept

- Corrosion in steel reinforcing bars in concrete could be affected by many metal and/or environmental factors, such as bacteria, conductivity, pH, oxygen content, temperature, condensation, corrosion products and deposits
- Unless the effects of all factors are known, the corrosion level of steel bars is difficult to quantify directly.
- If the corrosion process in steel bars is extended to a sensor through coating of the same material, the corrosion process of the coating can be accurately evaluated and correlated to that of the steel bars.

Genda Chen and Ying Huang. "A Hybrid Instrumented/Computational Modelling Framework with Lab-on-sensor Design and Calibration for Structural Behavior Monitoring," International Journal of Sustainable Materials and Structural Systems (http://www.inderscience.com/info/ingeneral/forthcoming.php?jcode=ijsmss).

Lab-on-sensor Theory

- For each electrochemical behavior, the lab-on-sensor theory includes three steps:
  - Extension of the behavior from a structural element to its nearby deployed sensor with a corrosion mechanism,
  - Calibration of the sensed parameter with the behavior of the sensor mechanism, and
  - Correlation of the behavior of the sensor mechanism with the behavior of the nearby structural element.

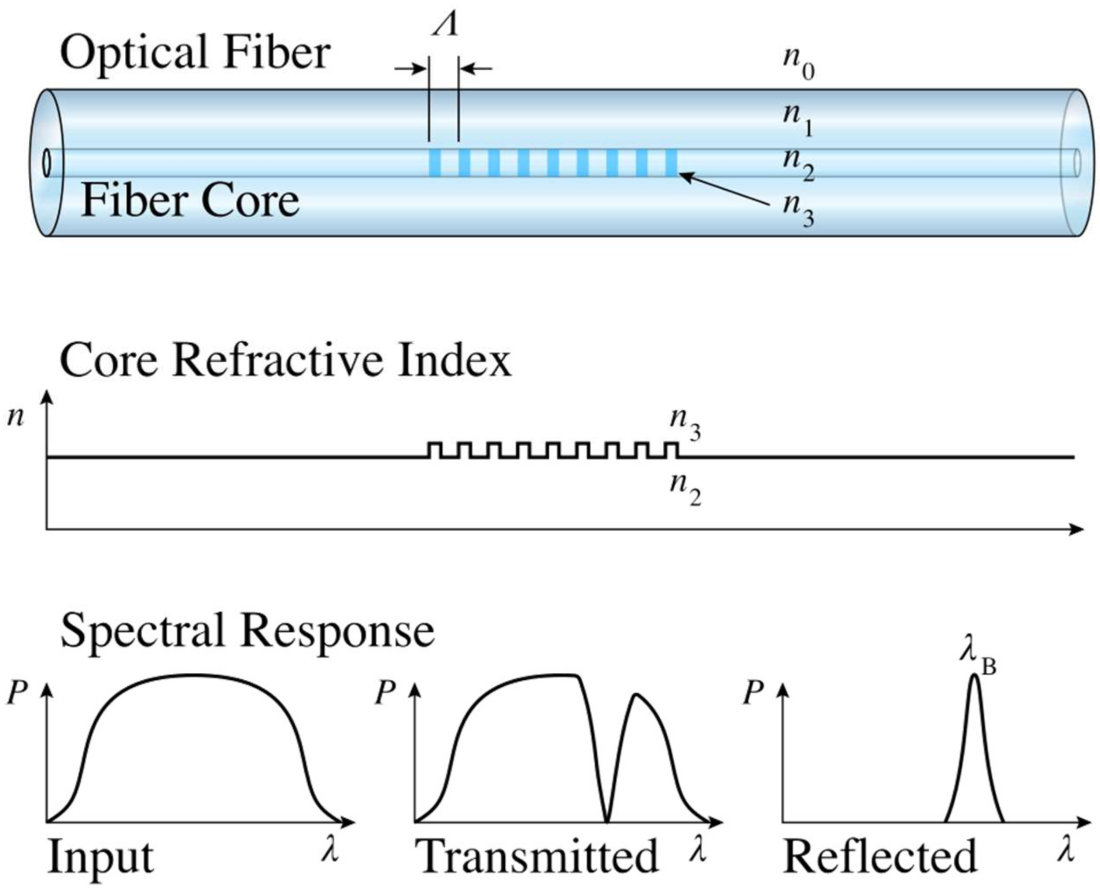


Lab-on-sensor with Fiber Gratings

- **The State of the Art**
  - **Previous Studies on Fiber Grating Sensors**
    - ✓ ***Fiber Bragg grating (FBG) based on the strain measurement in coating by Wenbin Hu***
    - ✓ ***Long-period fiber grating (LPFG) with nano iron particles based on change in refractive index by Ying Huang***
  - **Fe-C Coated LPFG Corrosion Sensor**
    - ✓ ***Direct and more sensitive in comparison with other optical fiber sensors***
    - ✓ ***Better than nano particle for adhesive and representative to rebar***
    - ✓ ***Combined with EIS or LPR tests to establish an accurate calibration relationship between resonant wavelength and mass loss***
    - ✓ ***Monitoring of different stages of corrosion in terms of reduction of thicknesses in coaxial steel tubes***

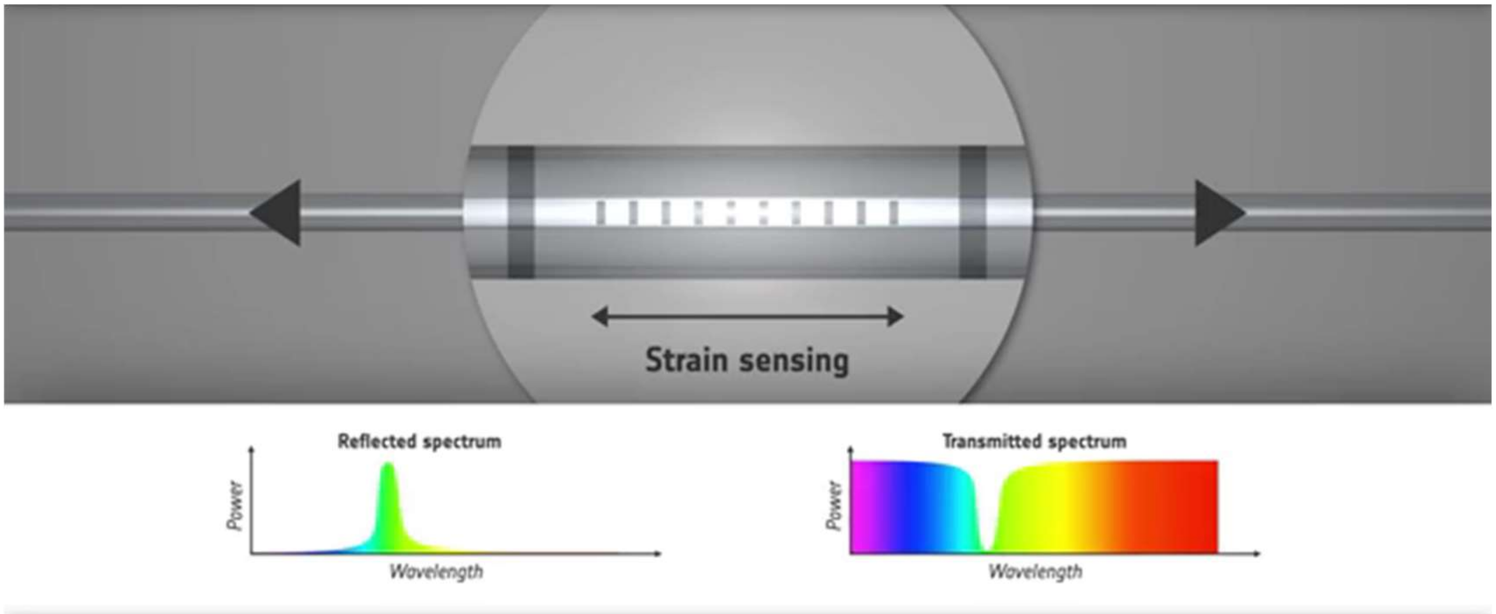
Short Period Fiber Gratings

- **Fiber Bragg Gratings (FBG)**
  - **Grating period usually less than 1 µm**
  - **All optical phenomena confined in fiber core**



Short Period Fiber Gratings

- **FBG Sensing for Strain and Temperature Effects**



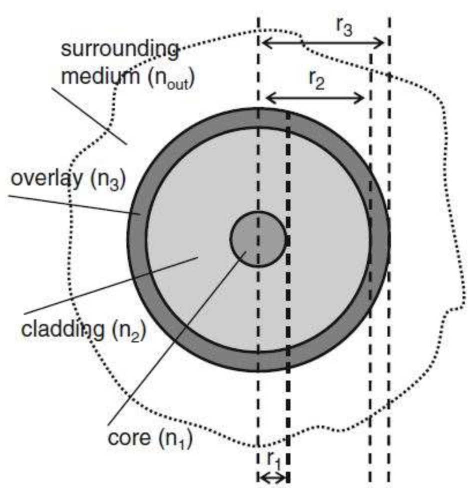
$$\lambda_B = 2n_e\Lambda$$

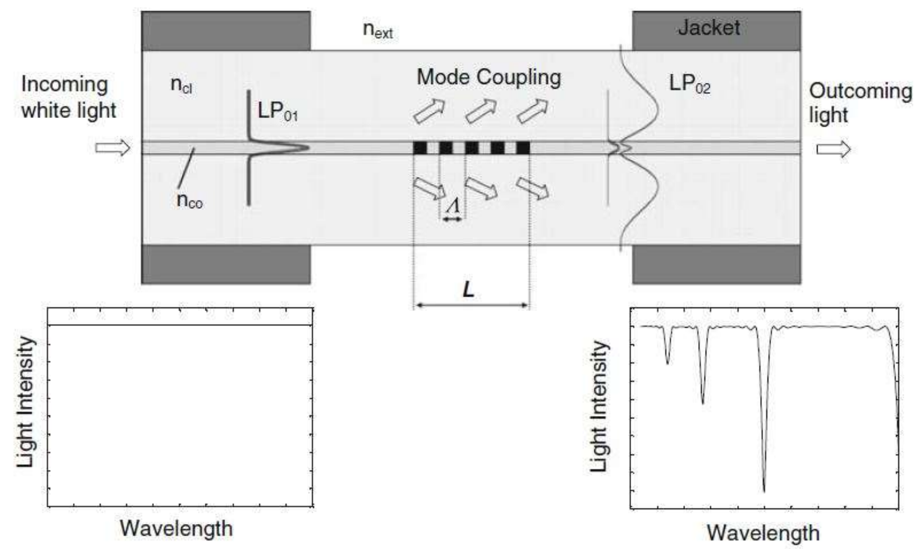
Bragg wavelength shift

Temperature or strain induced period change

Long Period Fiber Gratings (LPFG)

- **Grating period is in several hundred μm.**
- **Optical phenomenon happens in fiber core, cladding and surrounding medium.**





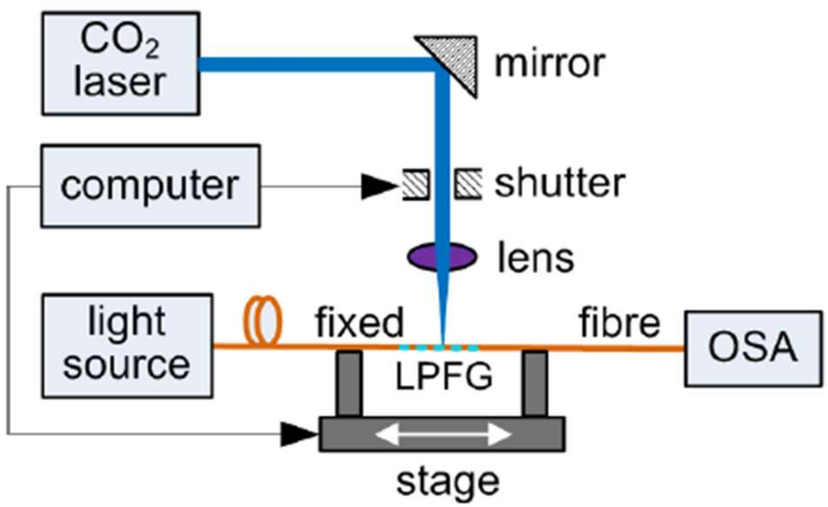
$$\lambda_{\mathrm{res},0j} = \left(n_{\mathrm{eff,co}} - n^{0j}_{\mathrm{eff,cl}}\right) \cdot \Lambda,$$

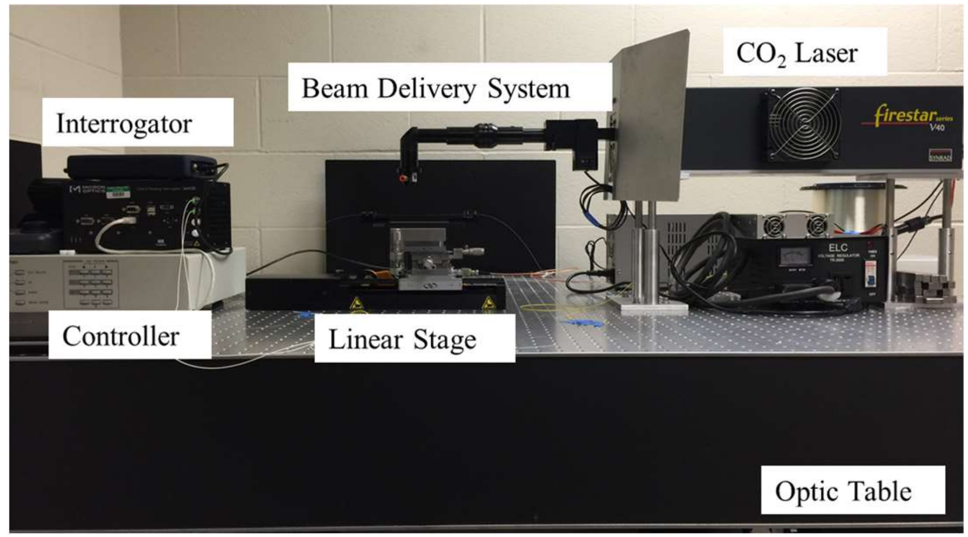
Change with the index of the surrounding medium (sensing layer)

Change with strain and temperature

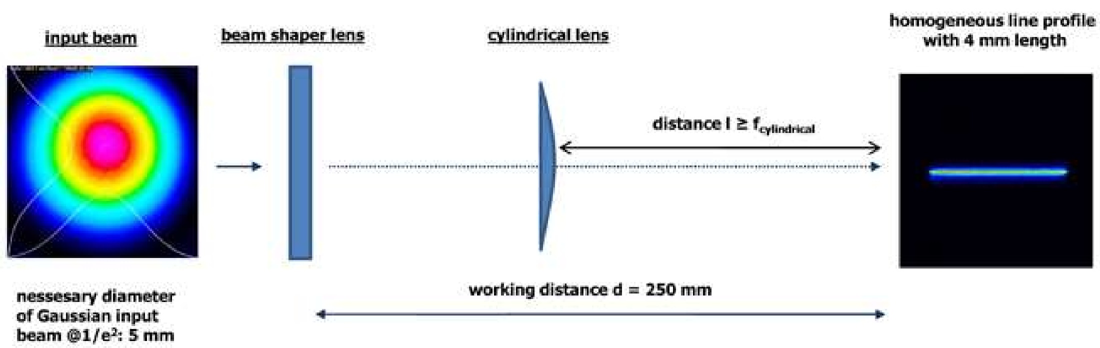
Long Period Fiber Gratings (LPFG)

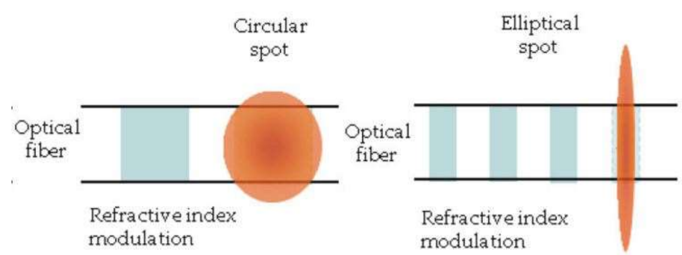
- **Design and Fabrication**
  - CO_2 laser grating. Line shape beam for higher resolution





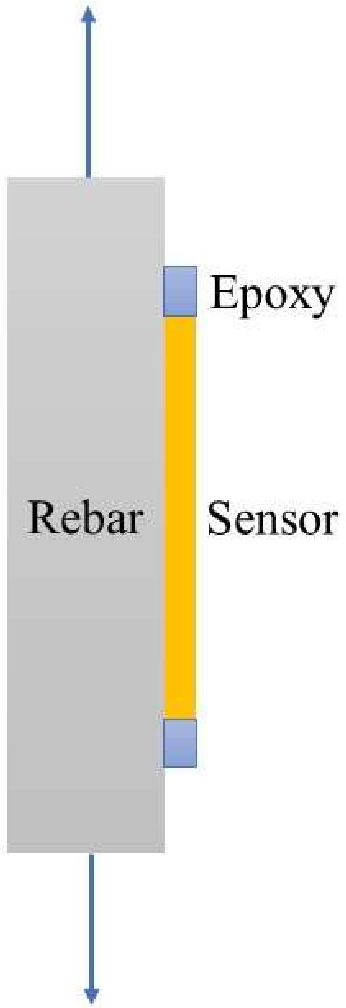
Laser grating system in SPAR Lab

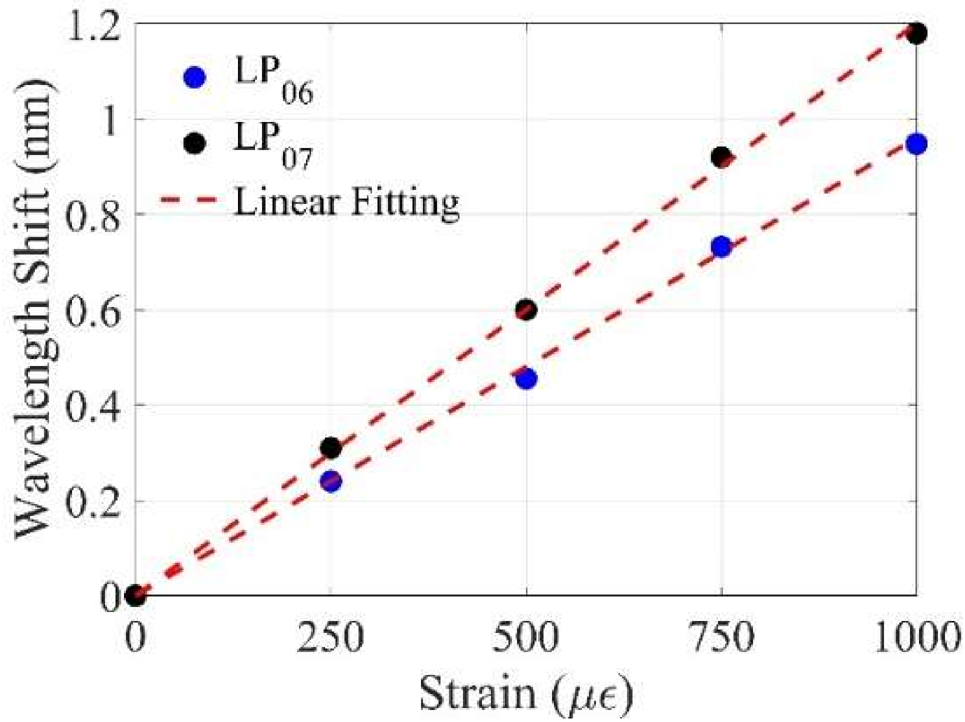




Long Period Fiber Gratings (LPFG)

- **Strain Sensing**



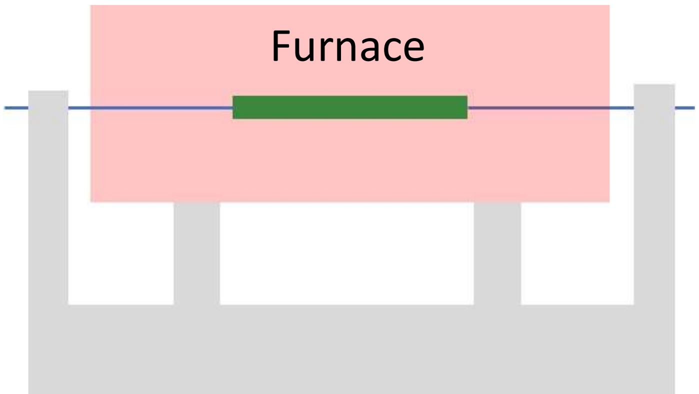


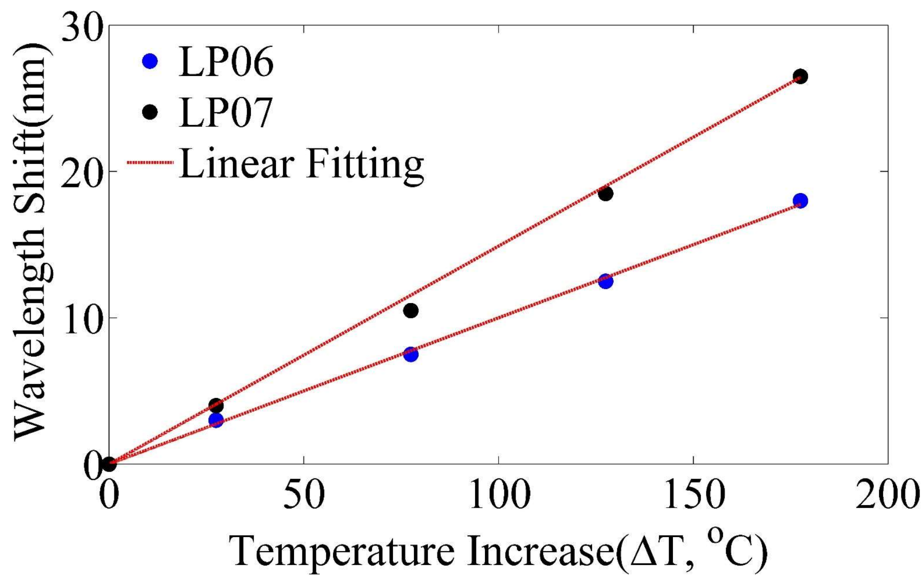
$$\Delta\lambda_{06} = 961.2\varepsilon, \quad R^2 = 0.97$$

$$\Delta\lambda_{07} = 1223.4\varepsilon, \quad R^2 = 0.98$$

Long Period Fiber Gratings (LPFG)

- **Temperature Sensing**

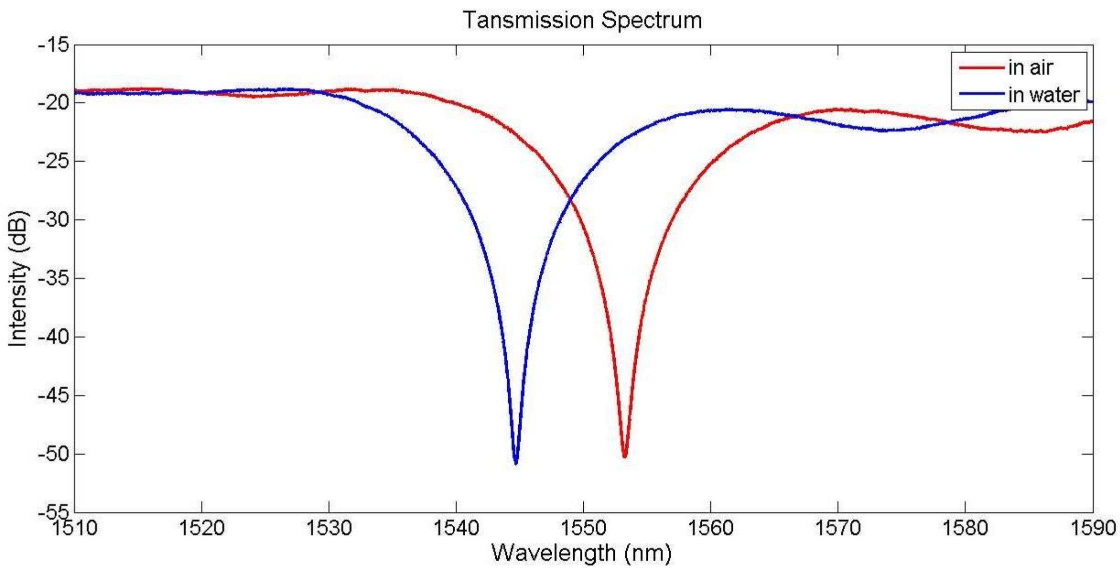


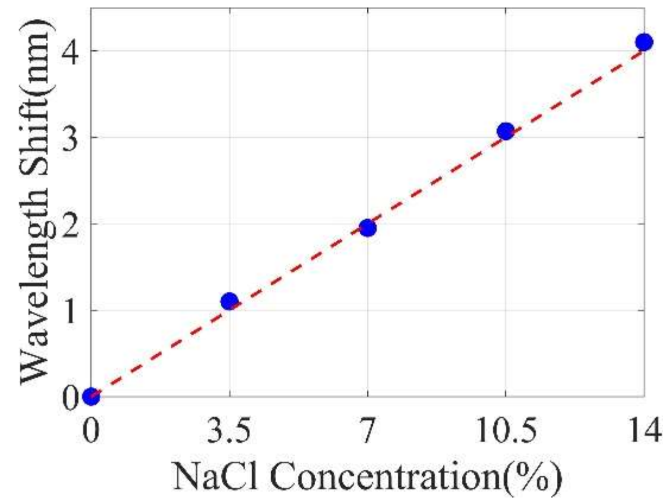


$$\Delta\lambda_{06} = 0.10\Delta T, R^2 = 0.99$$
$$\Delta\lambda_{07} = 0.15\Delta T, R^2 = 0.97$$

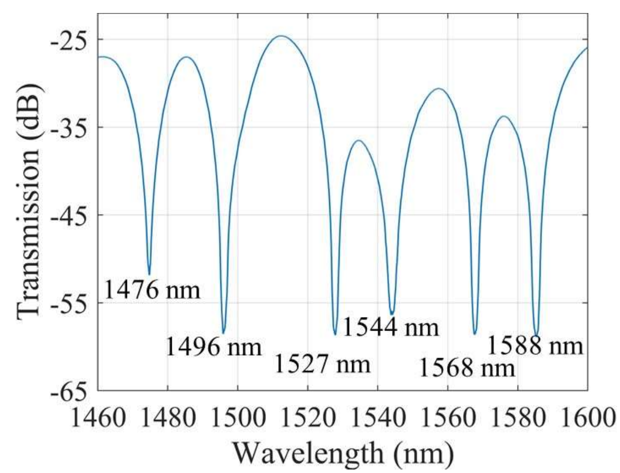
Long Period Fiber Gratings (LPFG)

- **Refractive Index Sensing**





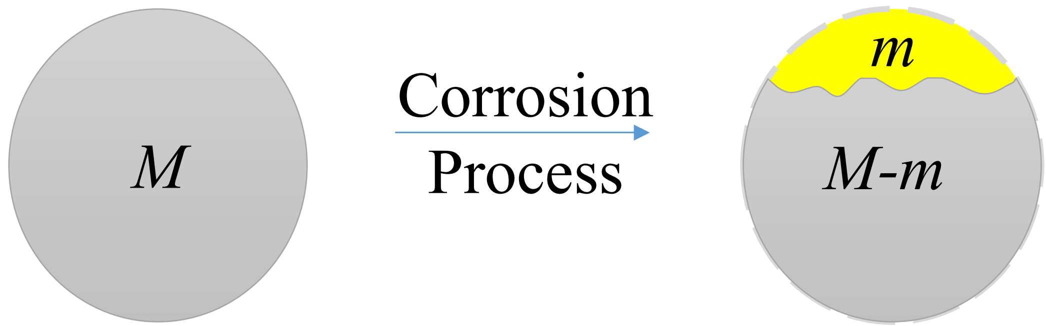
- **Multiplexed Sensors**
  - **Connect multiple LPFG sensors in one loop of optical fiber for multiplexed sensing**



LPFG Corrosion Sensors

- **Fe-C Coated LPFG for Mass Loss Measurement**

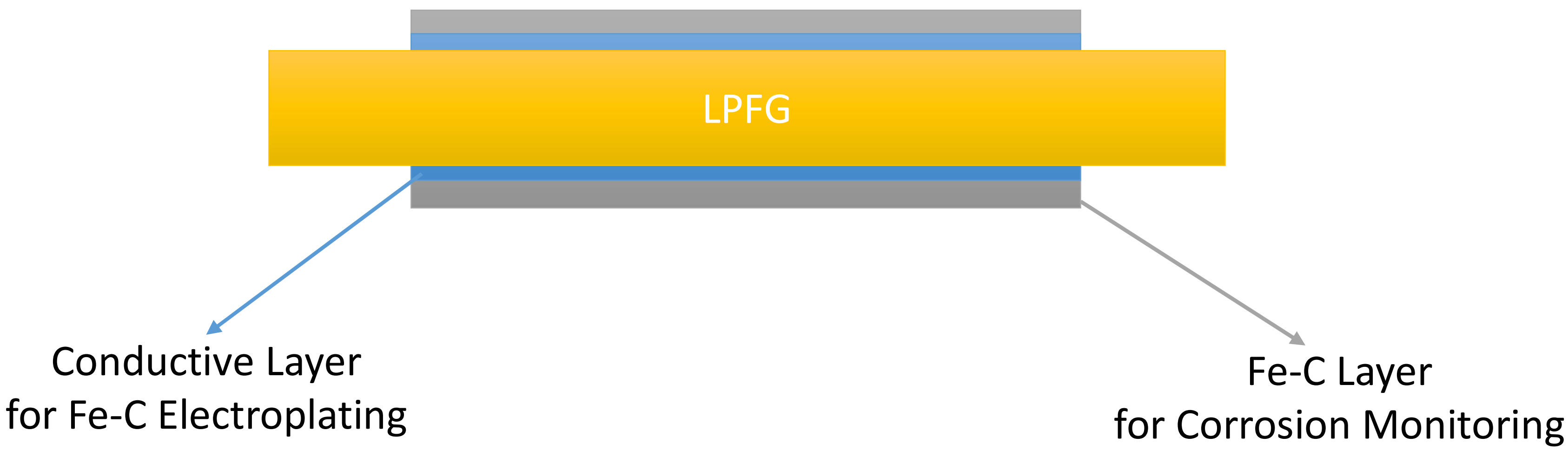
$$\eta = \frac{m}{M}$$



- ➢ **Directly correlated with the corrosion process**
- ➢ **Provide definitive information to engineers**
- ➢ **Not affected by other factors**

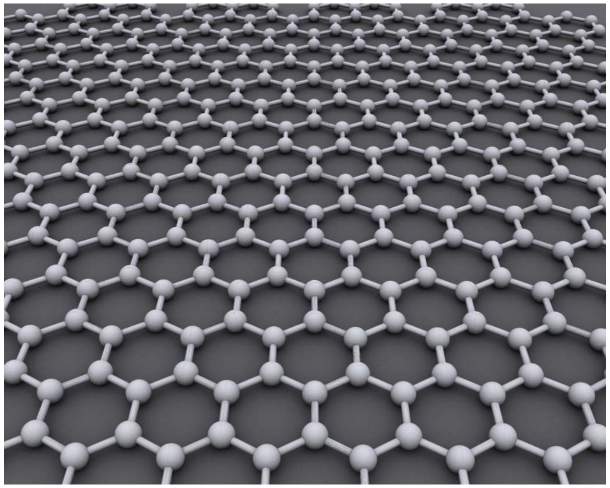
LPFG Corrosion Sensors

- **Fe-C Coated LPFG for Mass Loss Measurement**
  - **The Fe-C layer has the same chemical component ratio as the steel rebar so its corrosion process can be correlated to rebar corrosion in concrete**
  - **A conductive yet transparent layer is needed for Fe-C electroplating on LPFG while keep the sensor sensitive**



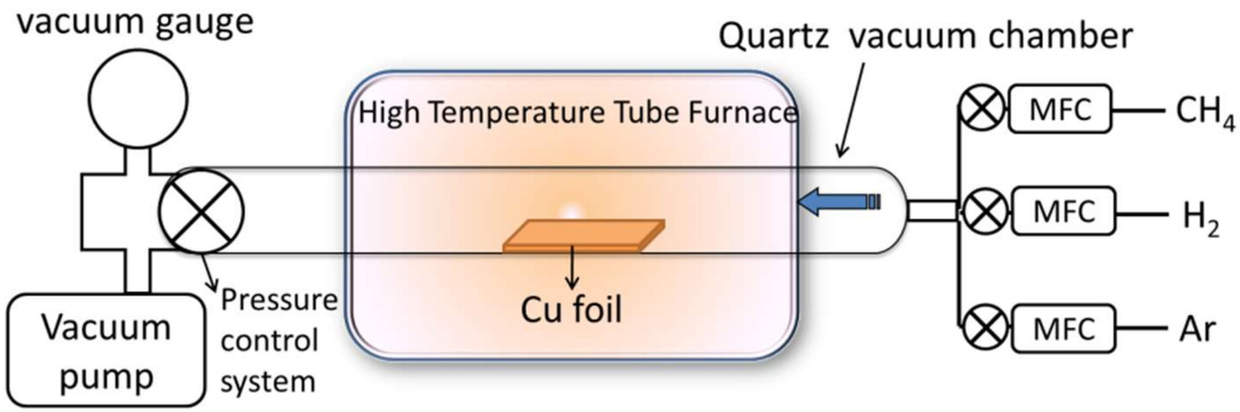
LPFG Corrosion Sensors

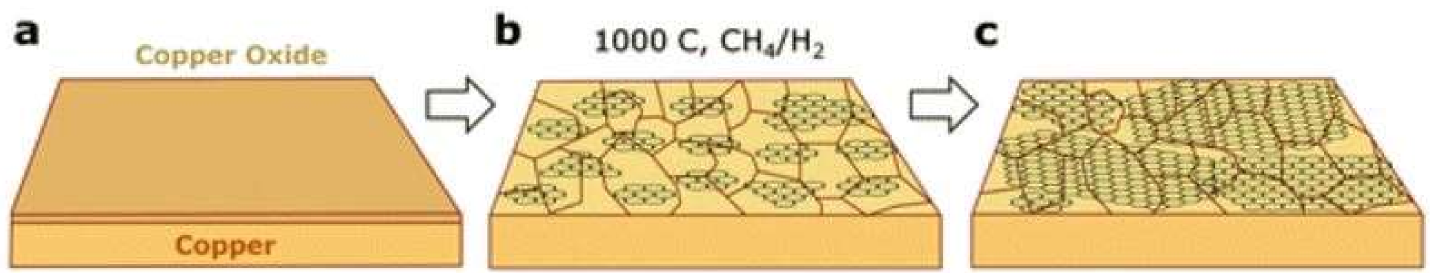
- Enhanced Fe-C Coated LPFG sensing with an Intermediate Graphene Film
- What is Graphene?
  - Graphene is an allotrope of carbon in the form of a two-dimensional, atomic-scale, hexagonal lattice in which one atom forms each vertex.
  - It is the basic structural element of other allotropes, including graphite, charcoal, carbon nanotubes and fullerenes.
- Unique Properties
  - High stiffness
  - Electrical conductivity
  - Optical transparency
  - 0.335 nm single layer thickness



LPFG Corrosion Sensors

- **Graphene Synthesis through Low Pressure Chemical Vapor Deposition (LPCVD)**

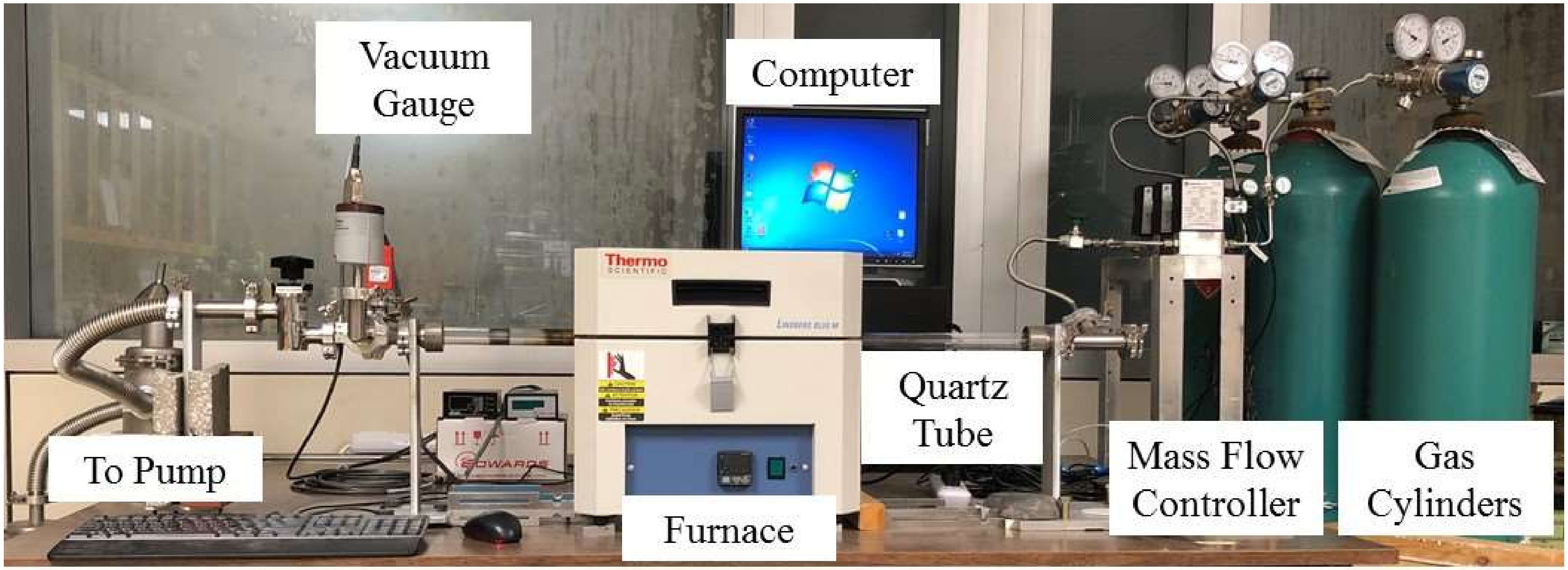




Schematic illustration of graphene growth on copper via LPCVD

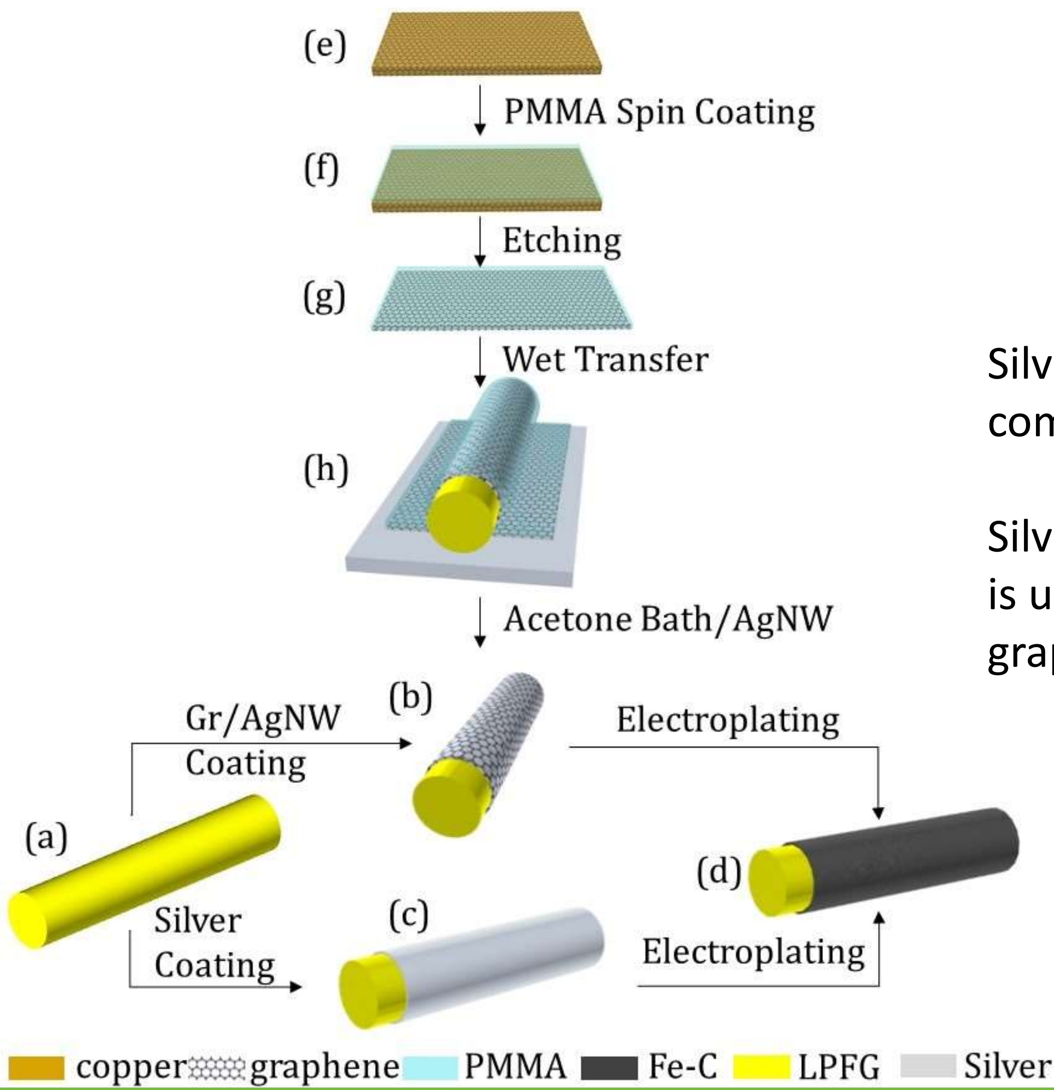
LPFG Corrosion Sensors

- LPCVD System



LPFG Corrosion Sensors

- **Fabrication of Fe-C Coated LPFG Sensors with a Graphene Film**

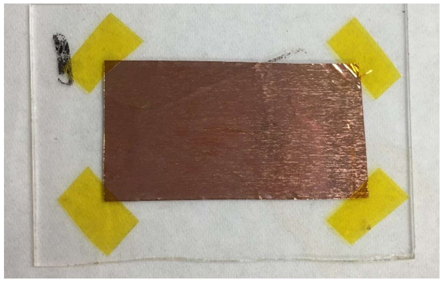


Silver layer is used for comparison

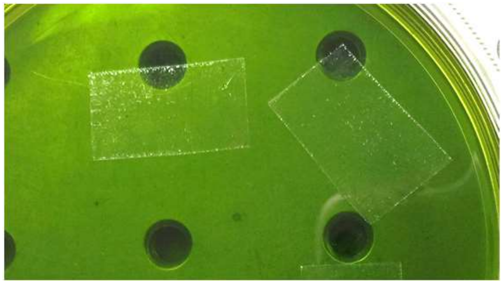
Silver nanowire (AgNW) is used to enhance the graphene conductivity

LPFG Corrosion Sensors

- **Fabrication of Fe-C Coated LPFG Sensors with a Graphene Film**



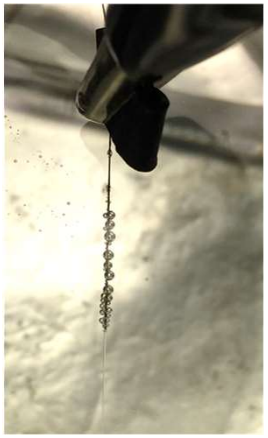
As-grown Gr on copper with PMMA coating



PMMA/Gr after etching

PMMA/Gr on DI water

PMMA/Gr coated on LPFG

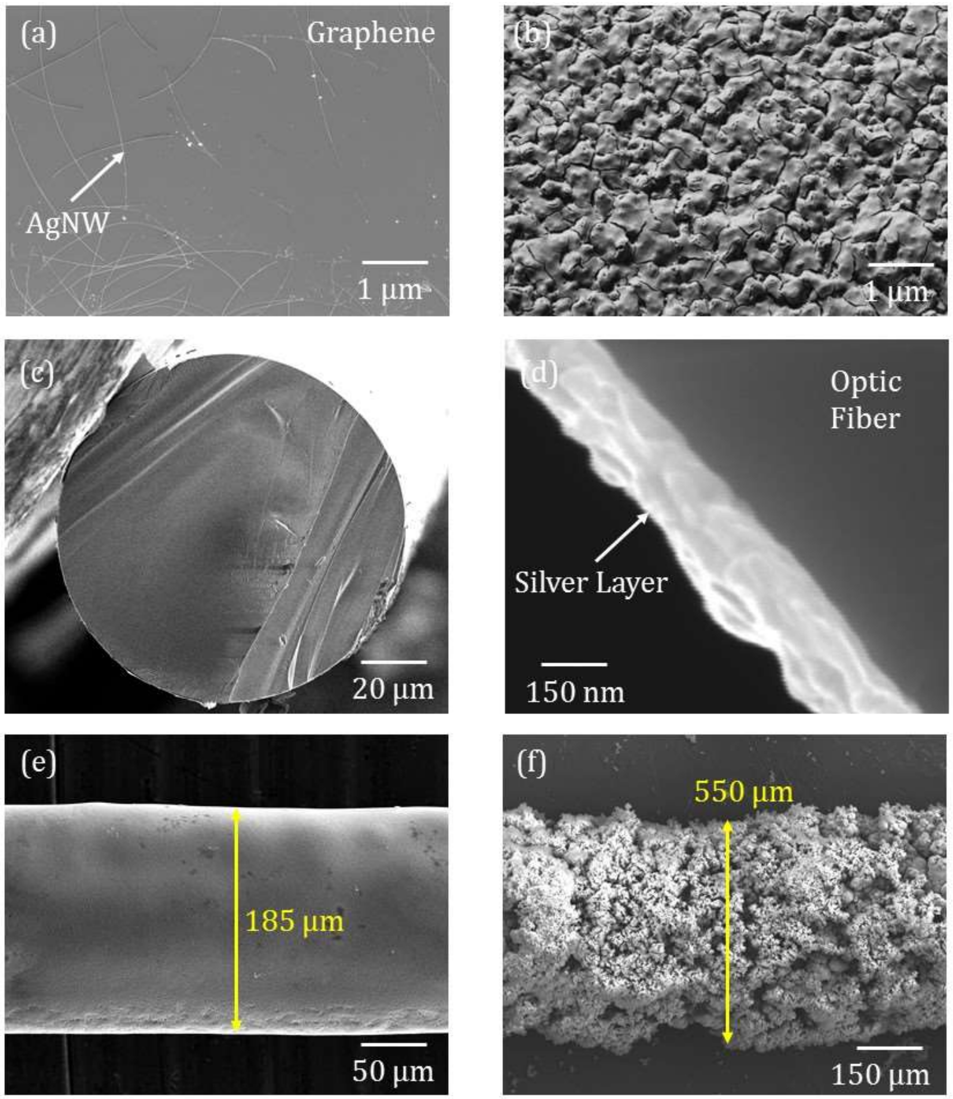


Electroplating

Fe-C coated LPFG

LPFG Corrosion Sensors

- **Characterization of the Coating Layer**



(a) Gr/AgNW composite

(b) Fe-C grains

(c) cross section of silver coated LPFG

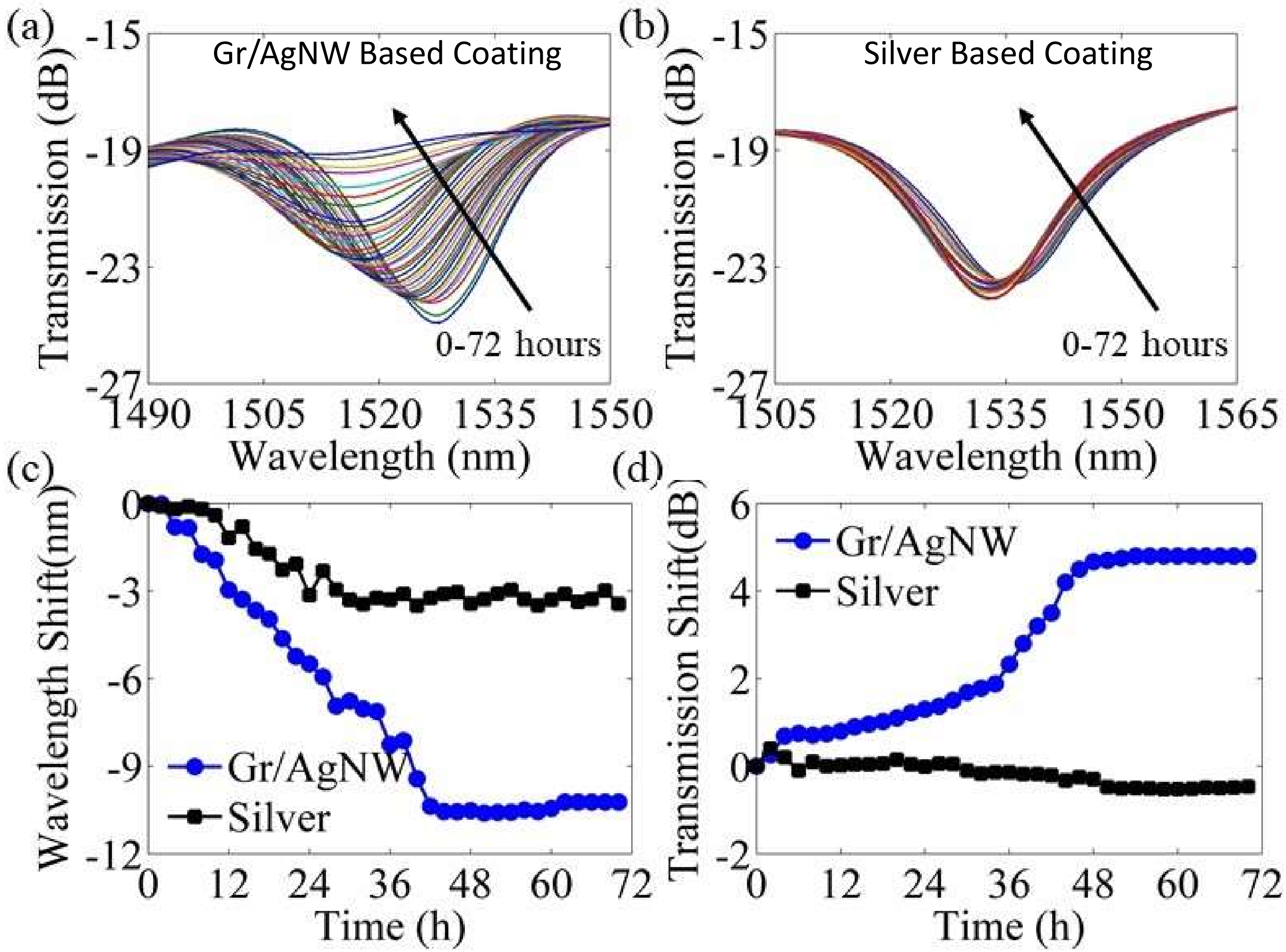
(d) thickness of silver layer

(e) Fe-C coated LPFG before and

(f) after 72 hours of immersion in 3.5 wt. % NaCl solution

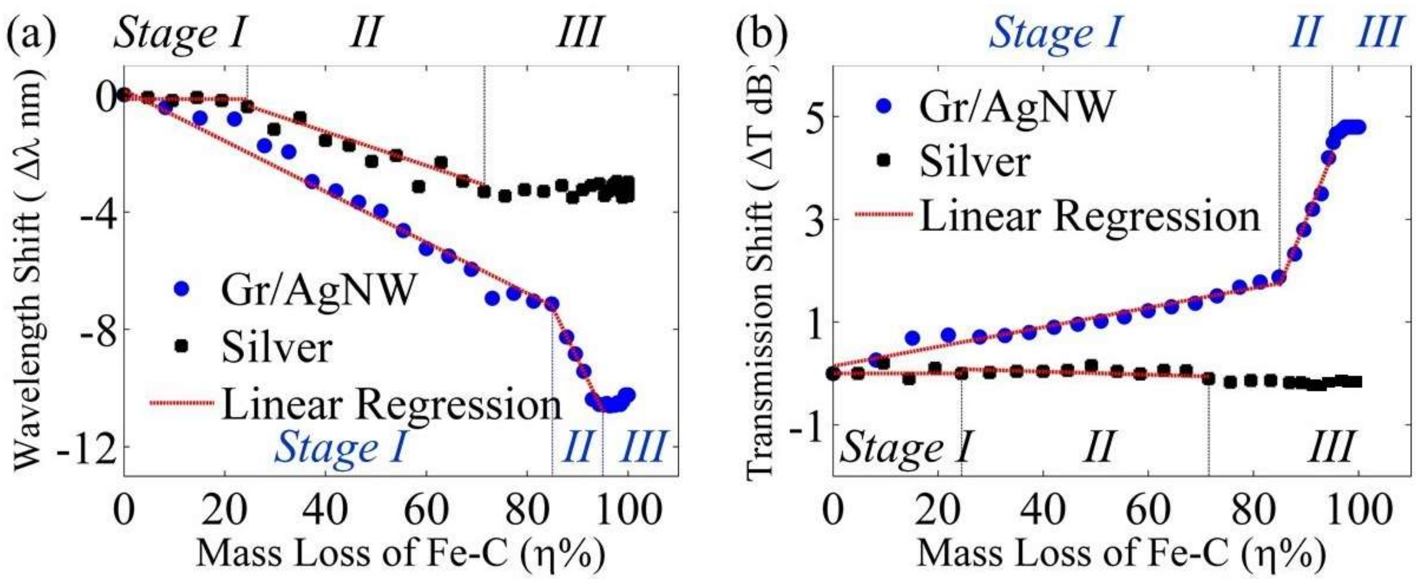
LPFG Corrosion Sensors

- **72 Hours of Corrosion Tests**



LPFG Corrosion Sensors

- **Correlation between Spectral Parameter and Mass Loss of a Fe-C Coated LPFG**



$\Delta\lambda_{GI}$= $-0.096\eta+0.69$ (R^2=0.90)

$\Delta\lambda_{GII}$= $-0.354\eta+22.81$ (R^2=0.98)

$\Delta\lambda_{SII}$= $-0.057\eta+0.84$ (R^2=0.89)

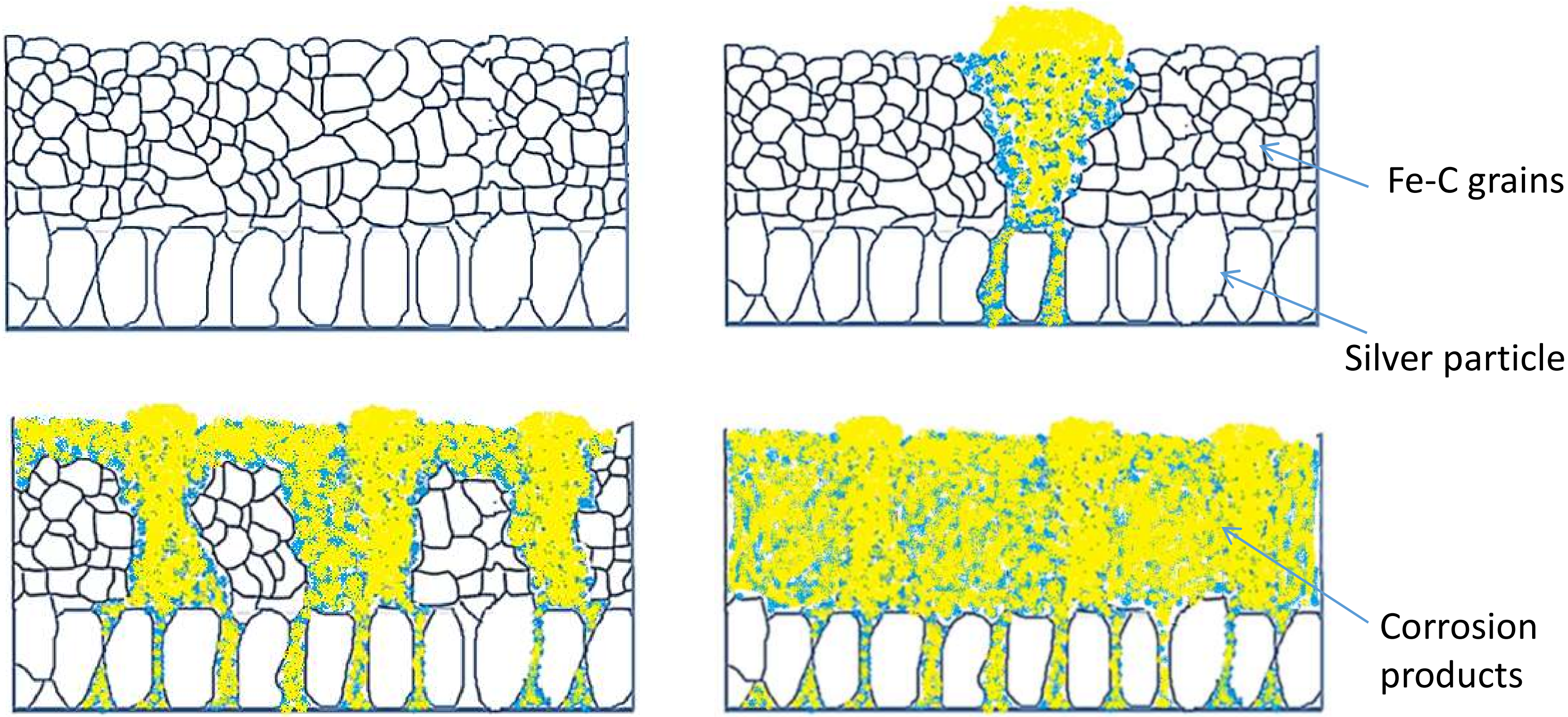
ΔT_{GI}= $0.019\eta+0.14$ (R^2=0.95)

ΔT_{GII}= $0.255\eta-19.93$ (R^2=0.97)

ΔT_{SII}= $-0.014\eta+1.03$ (R^2=0.94)

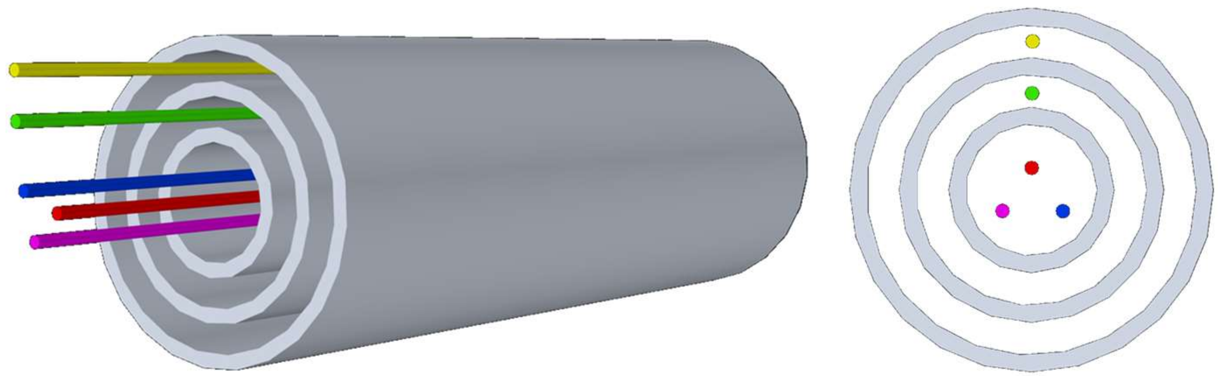
LPFG Corrosion Sensors

- **Schematic Illustration of Various Stages of Corrosion**



LPFG Corrosion Sensors

- **Design of an Integrated Sensor for Strain, Temperature and Mass Loss Measurement**



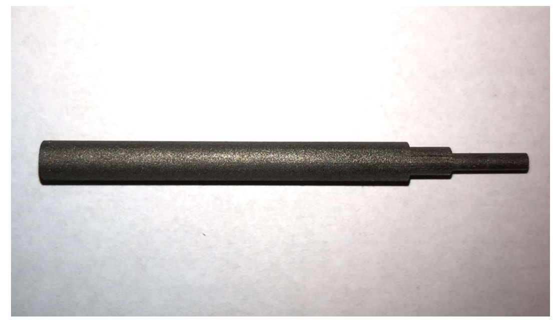
Steel tube extracted from steel members to be monitored for LPFG protection and monitoring of long-term corrosion at threshold levels

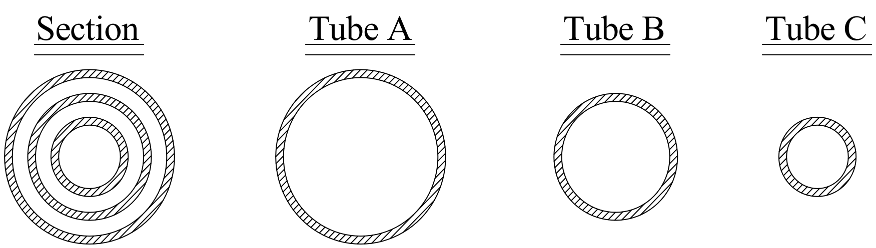
Three Fe-C coated LPFG sensors for the measurement of corrosion rate as each tube wall is completely penetrated.

LP06 and LP07 LPFG sensors for simultaneous measurement of strain and temperature, which are used to compensate corrosion-induced mass loss measurements with Fe-C coated LPFGs.

Long Period Fiber Gratings

- **Design of an Integrated Sensor for Strain, Temperature and Mass Loss Measurement**





Type	Tube A	Tube B	Tube C
OD (mm)	5.5	4.0	2.5
ID (mm)	5.0	3.5	2.0
Thickness (mm)	0.25	0.25	0.25
Length (cm)	5.0	5.0	5.0

LPFG Corrosion Sensors

- **Strain and Temperature Monitoring**
  - **Similar to Bare LPFG Sensors for Strain/Temperature Measurement**
- **Long-term Corrosion Monitoring**

Rebar before corrosion test

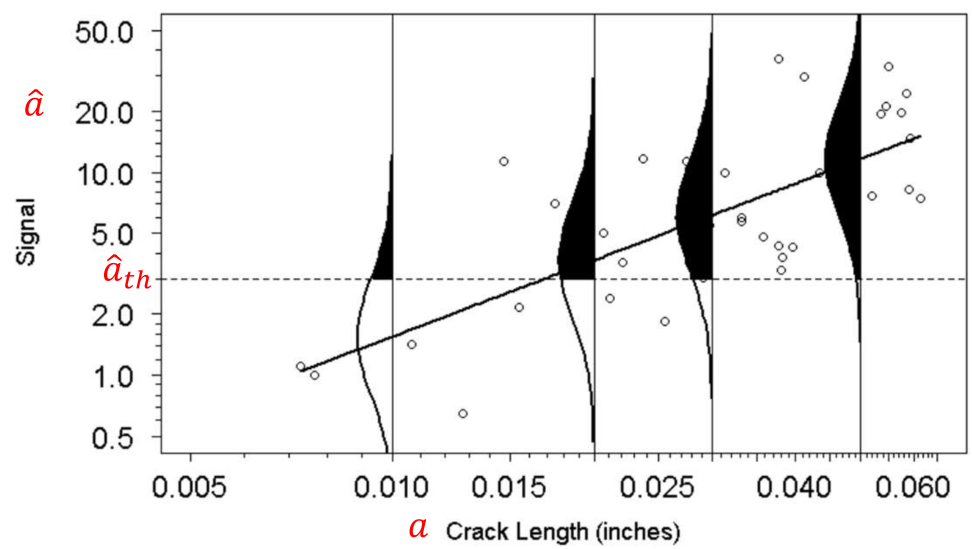
Single tube after penetration

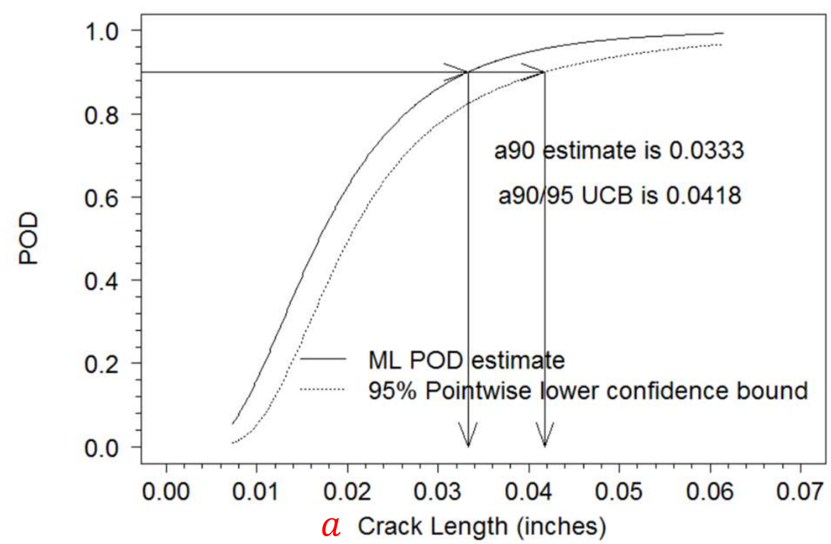
Rebar after corrosion test

Double tube after penetration

Probability of Detection (POD) in Corrosion

- **Basic Concepts**
  - **POD is a method used to determine the capability of an**
  - **inspection as a function of defect type and defect size**





$$POD(a) = \frac{n_d}{n}$$

a_{90} - target size at 90% POD

$a_{90/95}$ - a 95% confidence value for a_{90}

Probability of Detection (POD) in Corrosion

- **Two Methods for POD Calculation**

$$POD(length) = \Pr(Response > a_{th}) = 1 - \Phi_{\text{Norm}}(z)$$

(a) $\hat{a}$ *Versus a* Method

$$Response_i = \beta_0 + \beta_1 \times length_i + \varepsilon_i$$

$$z = \frac{\hat{a}_{th} - (\beta_0 + \beta_1 \times length)}{\sigma_\varepsilon}$$

- Relatively simple in computation
- More precise in estimation for two parameters only
- Dependent of an assumption on the distribution of detectable crack sizes

(b) Random Effects Generalization Method

$$Response_{ij} = \beta_{0i} + \beta_{1i}(length - \overline{length}) + \varepsilon_{ij}$$

$$z = \frac{\hat{a}_{th} - (\mu_{\beta_0} + \mu_{\beta_1}(length - \overline{length}))}{(\sigma_{\beta_0}^2 + (length - \overline{length})^2 \sigma_{\beta_1}^2 + 2(length - \overline{length})\sigma_{\beta_0}\sigma_{\beta_1}\rho + \sigma_\varepsilon^2)^{1/2}}.$$

- Relatively complicated in computation
- More efficient in the use of data, especially when available to check model assumptions
- More robust to departures from model assumptions

Probability of Detection (POD) in Corrosion

- **POD Analysis**

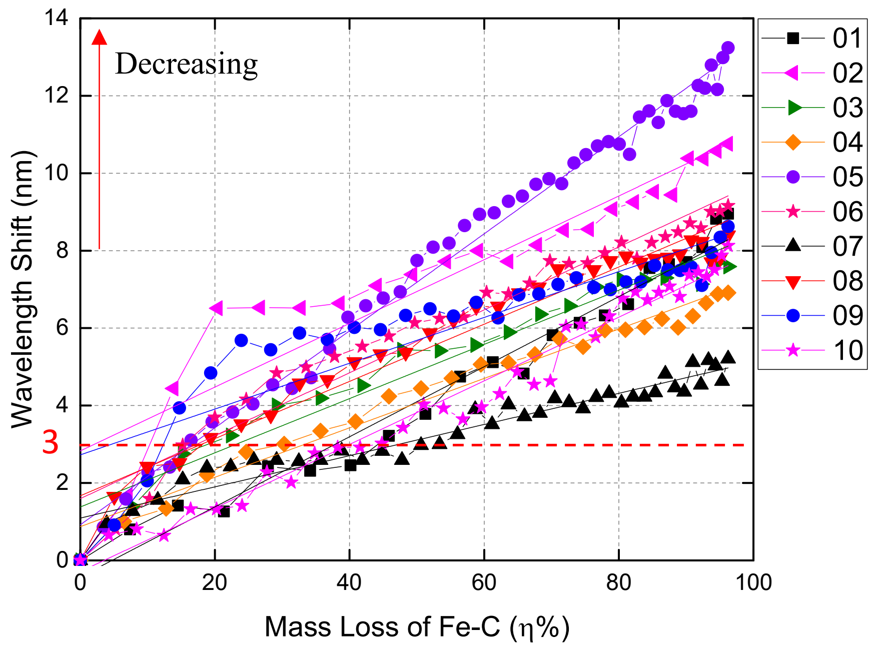


Fig. (a) Wavelength shift with mass loss of Fe-C coating

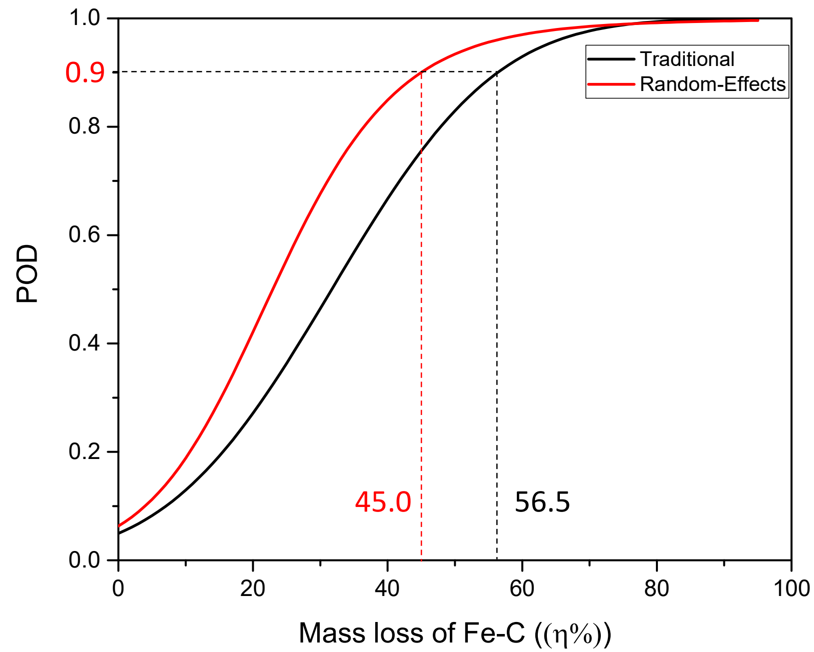


Fig. (b) Two POD curves developed from two methods

Concluding Remarks

- Optical fiber sensors provide an effective multi-parameter measurement tool for infrastructural applications.
- The CO_2 laser grating system produces LPFG sensors that can be used for strain, temperature and refractive index sensing.
- The low pressure chemical vapor deposition (LPCVD) system helps to synthesize as-grown monolayer graphene on a copper foil. The graphene layer can be transferred in wet condition via a PMMA film onto a target substrate. It can be strengthened by silver nanowires for improved mechanical strength and electrical conductivity.

Concluding Remarks

- Compared to the silver-based sensor, the Gr/AgNW-based corrosion sensor increased sensitivity by 1.9 times in Stage I and 7.2 times in Stage II due to its high optical transparency. The service life was also increased by 2.1 times.
- The integrated sensor with three steel tubes and five LPFG sensors placed inside the tubes is rugged for field applications and effective for both long-term and short-term corrosion monitoring.

Acknowledgement

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- Thanks are due to graduate students (Ying Huang, Yizheng Chen, Fujian Tang, Chuanrui Guo, Liang Fan, Ying Zhuo, and Pengfei Ma)