INSPIRE

INSPECTING AND PRESERVING INFRASTRUCTURE THROUGH ROBOTIC EXPLORATION

In-line Long Period Grating and Brillouin Scattering Fiber Optic Sensors for Strain, Temperature, Chloride Concentration, and Steel Mass Loss Measurement in Bridge Applications

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Outline

- Project objectives
- LPFG based integrated sensing system for life-cycle corrosion monitoring (chloride ion and mass loss) of nearby steel members with temperature and strain compensation
- Maximum number of LPFG sensors for multiplex sensing
- Interference between the LPFG sensor and pulse pre-pump Brillouin optical time domain analysis (PPP-BOTDA) measurement
- Concluding remarks
- Acknowledgement

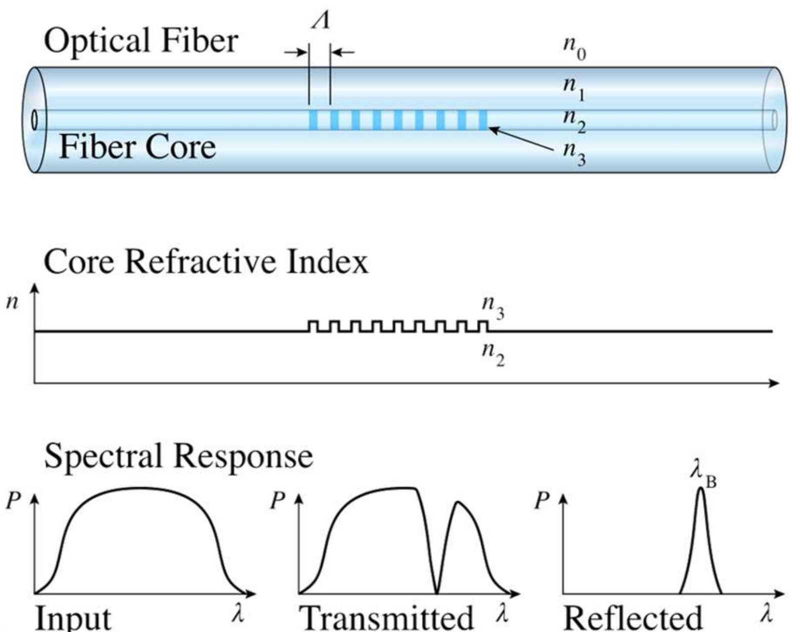
Project objectives

- Develop a physically and optically protected LPFG strain sensor that is hermetically packaged in a fused silica capillary tube
- Develop a Fe-C coated LPFG sensor for life-cycle corrosion monitoring (chloride ion and mass loss) of nearby steel members
- Understand how many LPFG sensors of different types and wavelengths can be multiplexed to measure multiple parameters for the monitoring of large-scale bridges
- Understand potential interference between the LPFG sensor interrogation and the pulse pre-pump Brillouin optical time domain analysis (PPP-BOTDA) measurement

Long Period Fiber Grating (LPFG): Design And Fabrication

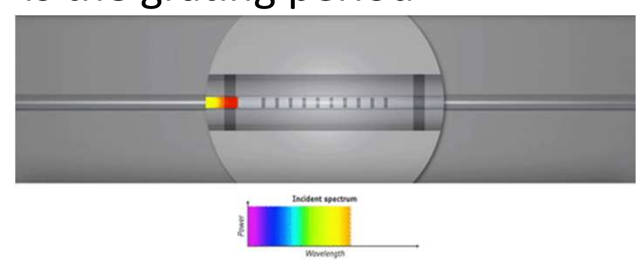
- **Fiber grating for sensing, signal processing**
  - **Periodically modulate the refractive index of the fiber core**

- **Fiber Bragg Grating (FBG)**
  - **Grating period usually less than 1 micrometer**
  - **All optical phenomenon confined in fiber core**



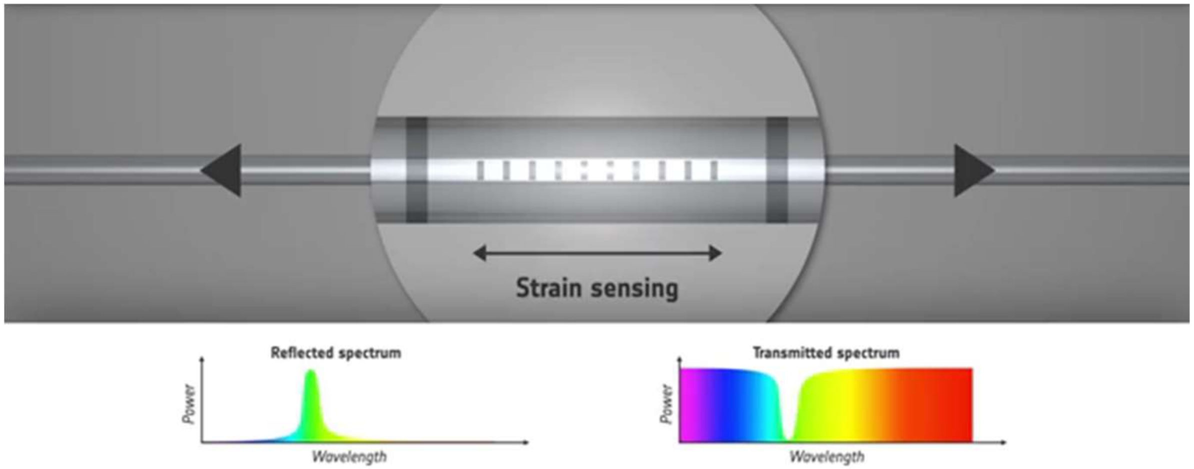
$$\lambda_B = 2n_e\Lambda$$

λ_B is the Bragg (reflection) wavelength
n_e is the refractive index of the grating
Λ is the grating period



Long Period Fiber Grating: Design And Fabrication

- **Strain and temperature sensing of FBG**



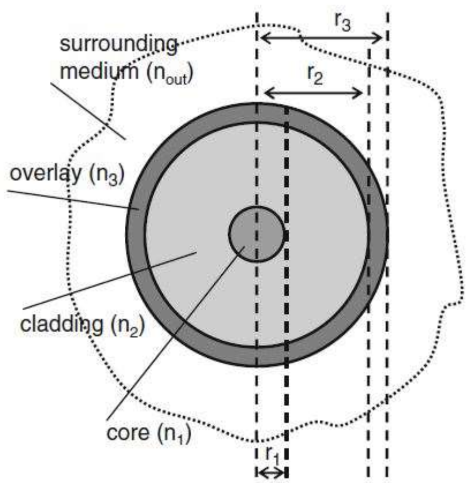
$$\lambda_B = 2n_e\Lambda$$

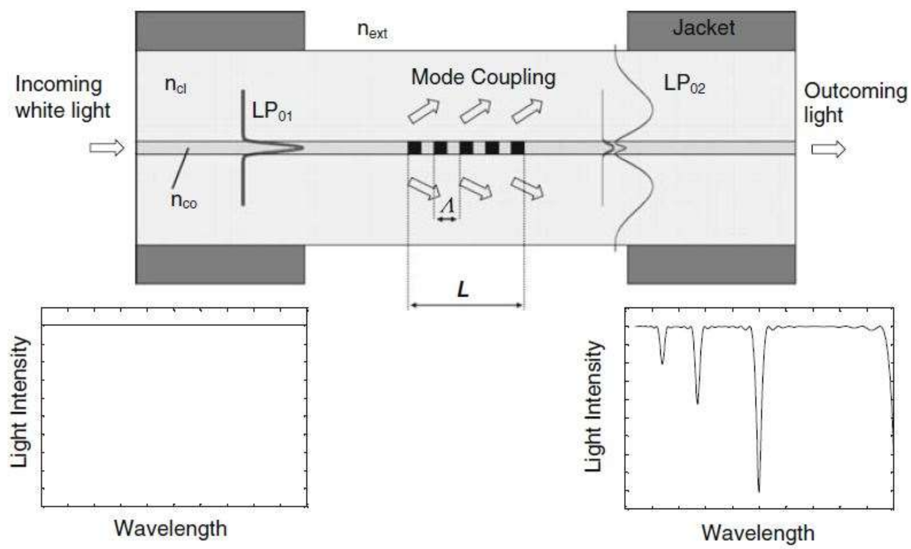
Bragg wavelength shift

Temperature or strain induced period change

Long Period Fiber Grating: Design And Fabrication

- **Long Period Fiber Grating (LPFG)**
  - **Grating period usually between several hundred micrometers**
  - **Optical phenomenon happens in fiber core, cladding and surrounding medium**





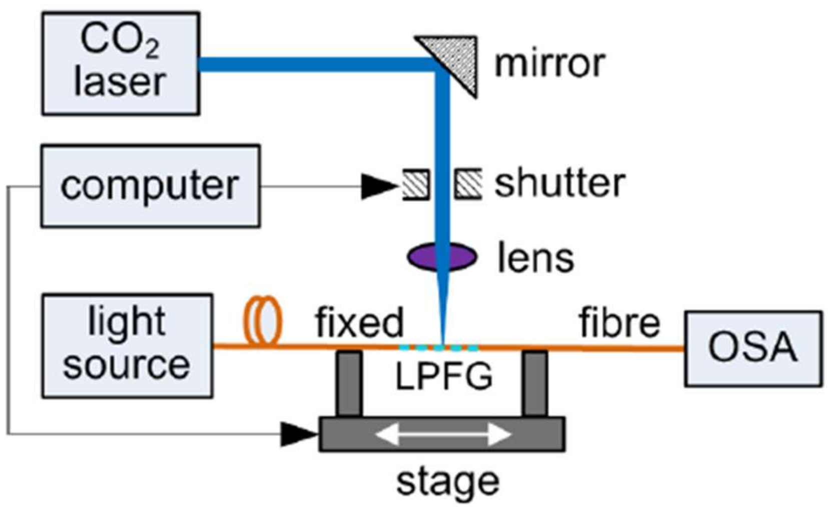
$$\lambda_{\text{res},0j} = \left(n_{\text{eff,co}} - n_{\text{eff,cl}}^{0j}\right) \cdot \Lambda,$$

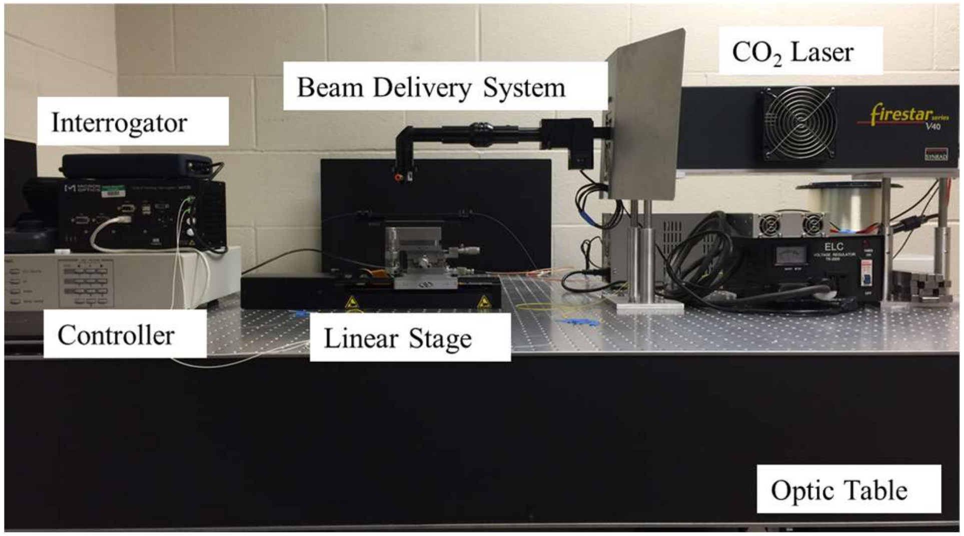
Change with the index of the surrounding medium (sensing layer)

Change with strain and temperature

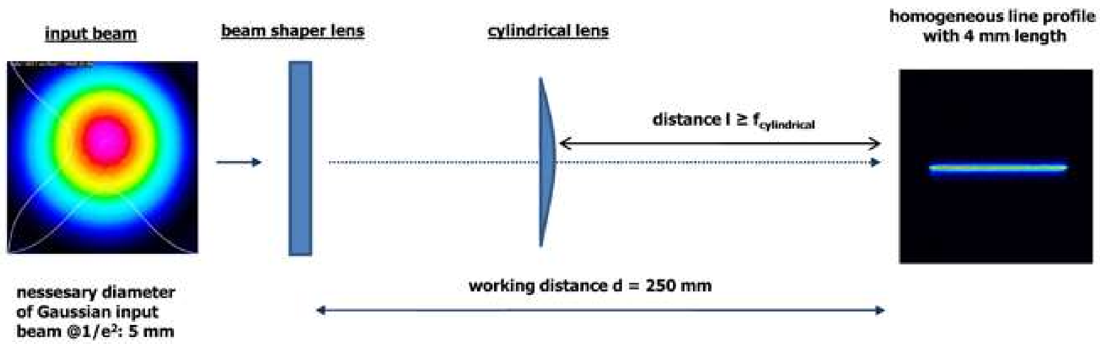
Long Period Fiber Grating: Design And Fabrication

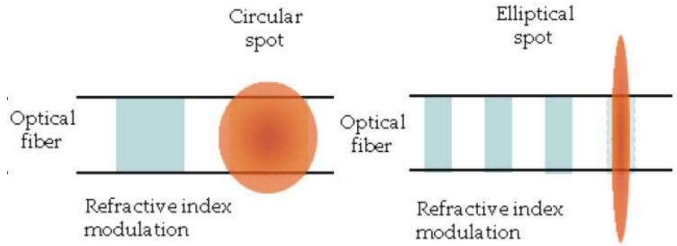
- **Fabrication of LPFG**
  - CO_2 laser grating. Line shape beam for higher resolution





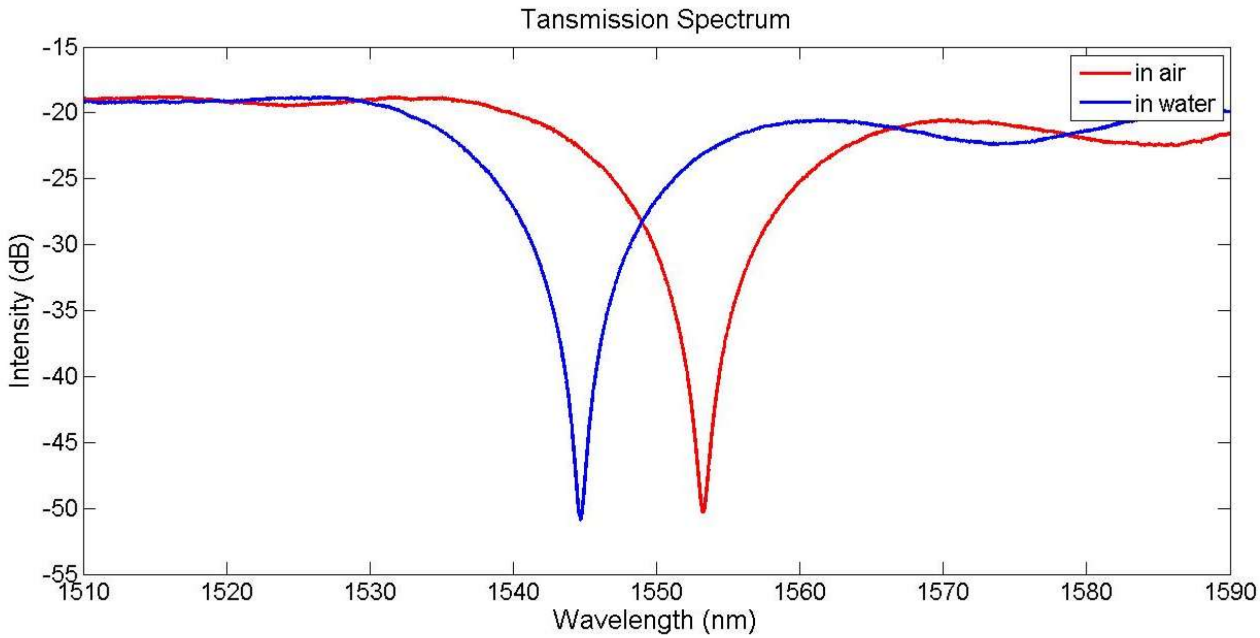
Laser grating system in SPAR Lab

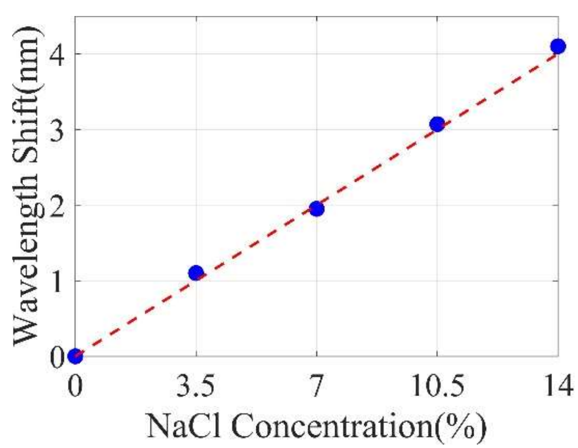




LPFG for strain, temperature and refractive index sensing

- **Refractive Index Sensing**





LPFG for strain, temperature and refractive index sensing

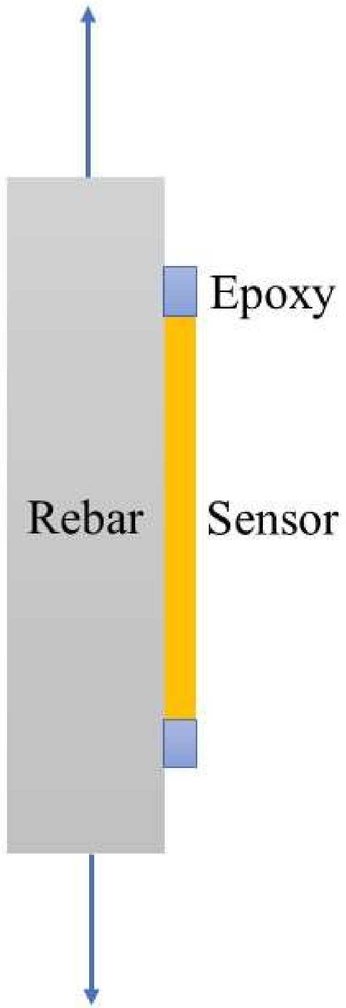
$$\lambda_{res,0j} = \left(n_{eff,co} - n^{0j}_{eff,cl}\right) \cdot \Lambda,$$

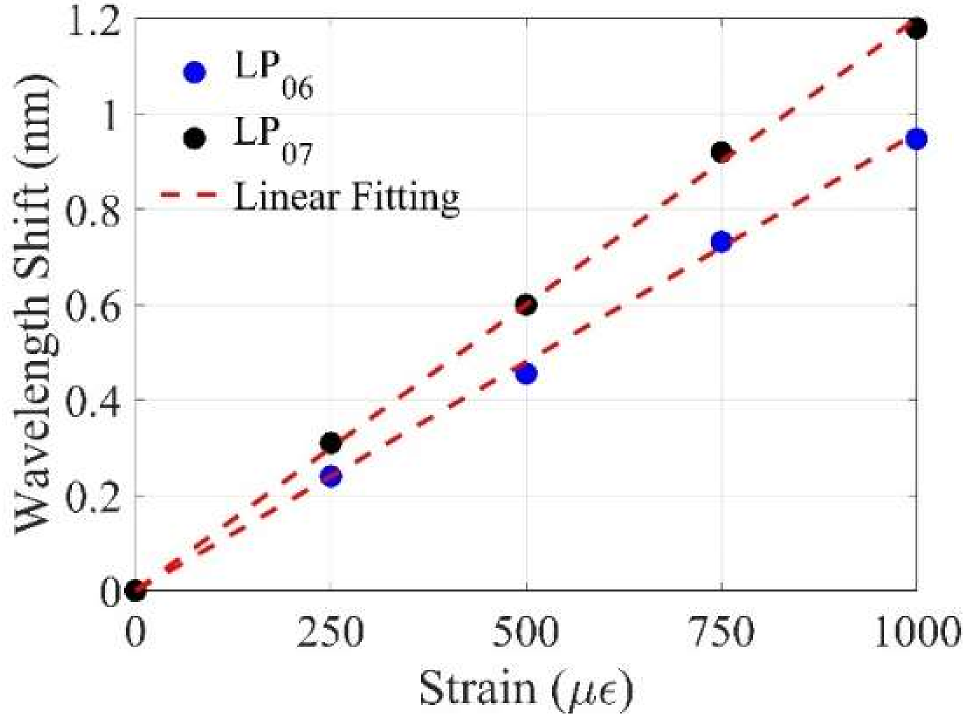
- Grating Period, Λ
  - Strain
  - Temperature
  - Pressure

- Overlay Refractive Index, $n^{0j}_{eff,cl}$
  - pH
  - Liquid Level
  - Corrosion

LPFG for strain, temperature and refractive index sensing

- **Strain Sensing**



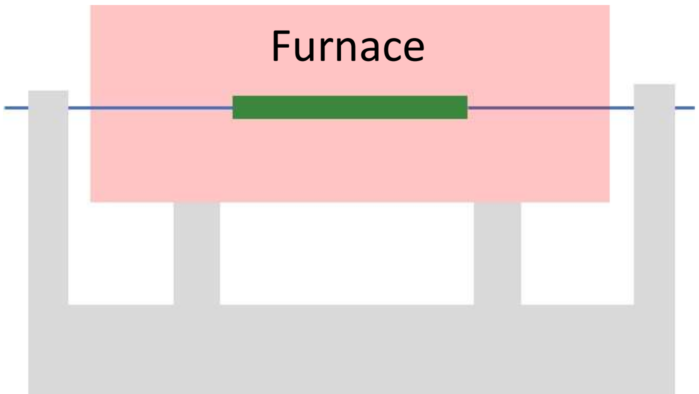


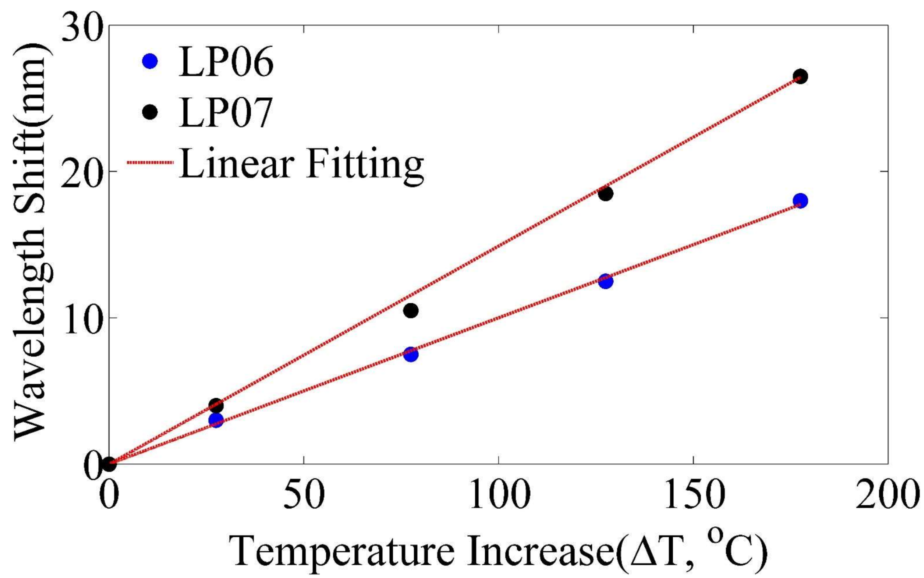
$$\Delta\lambda_{06} = 961.2\varepsilon, \quad R^2 = 0.97$$

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

LPFG for strain, temperature and refractive index sensing

- **Temperature Sensing**

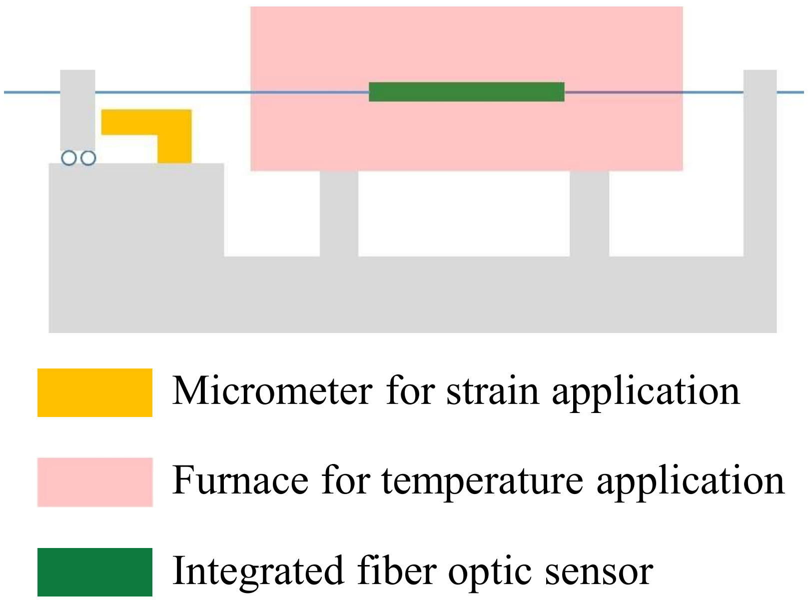


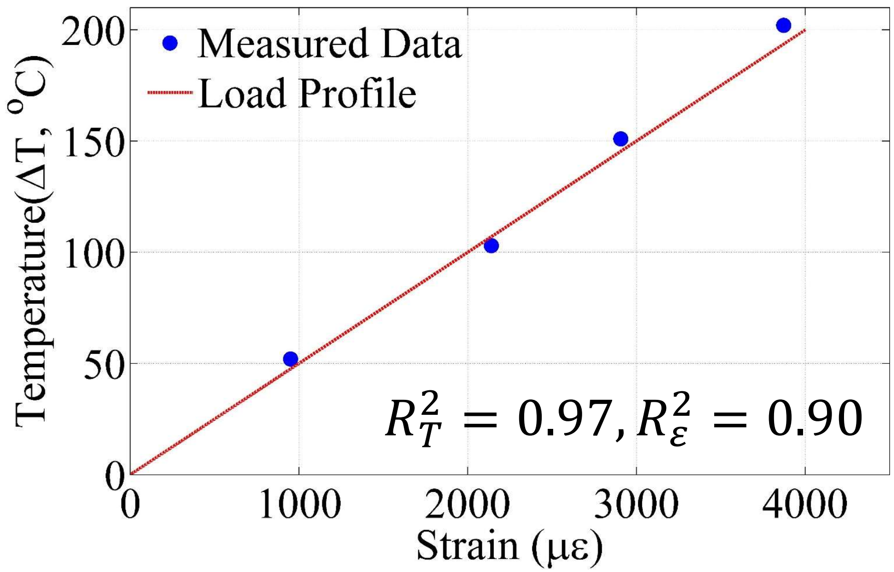


$$\Delta\lambda_{06} = 0.10\Delta T, R^2 = 0.99$$
$$\Delta\lambda_{07} = 0.15\Delta T, R^2 = 0.97$$

Integrated Sensor for Strain, Temperature and corrosion measurement

- **Simultaneous Measurement of Strain and Temperature**



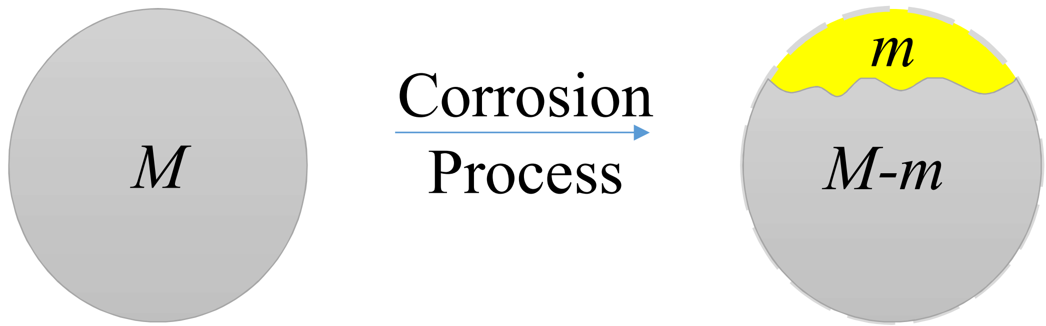


$$\begin{Bmatrix} \Delta\lambda_{06} \\ \Delta\lambda_{07} \end{Bmatrix} = \begin{Bmatrix} \alpha_{06} & k_{06} \\ \alpha_{07} & k_{07} \end{Bmatrix} \begin{Bmatrix} \Delta T \\ \varepsilon \end{Bmatrix}$$

Fe-C coated LPFG for corrosion induced mass loss measurement

- **Mass Loss as Direct Parameter for Corrosion Monitoring**

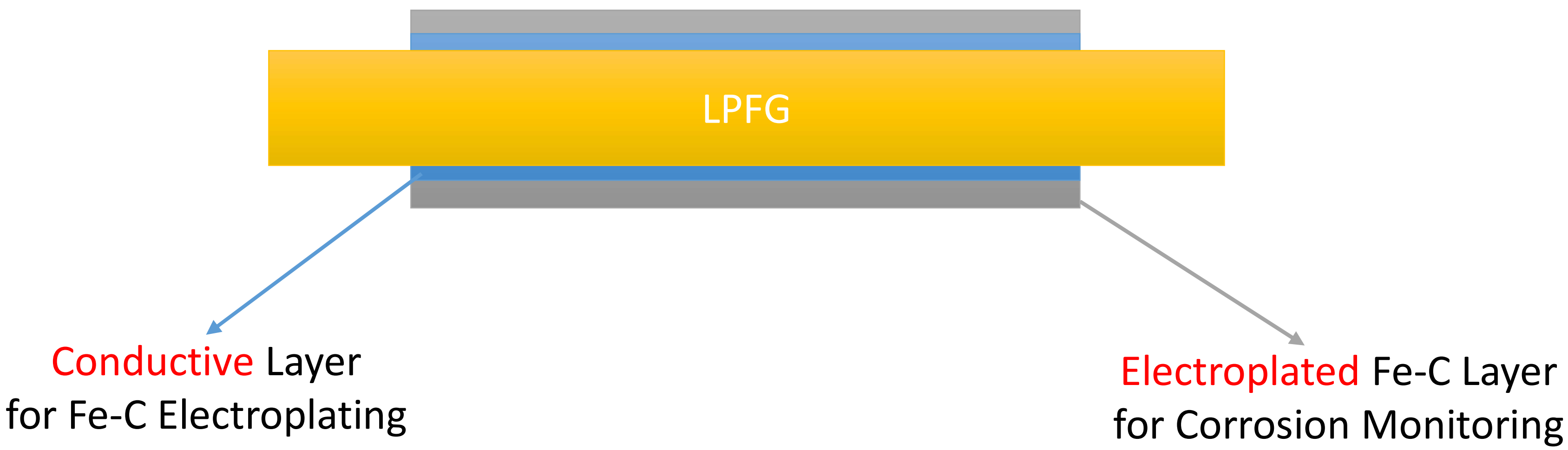
$$\eta = \frac{m}{M}$$



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

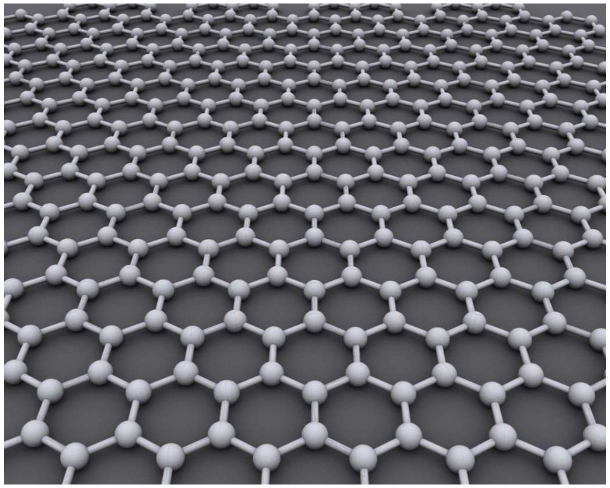
Fe-C coated LPFG for corrosion induced mass loss measurement

- **Fe-C Coated LPFG Corrosion Sensor**
  - ➢ 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



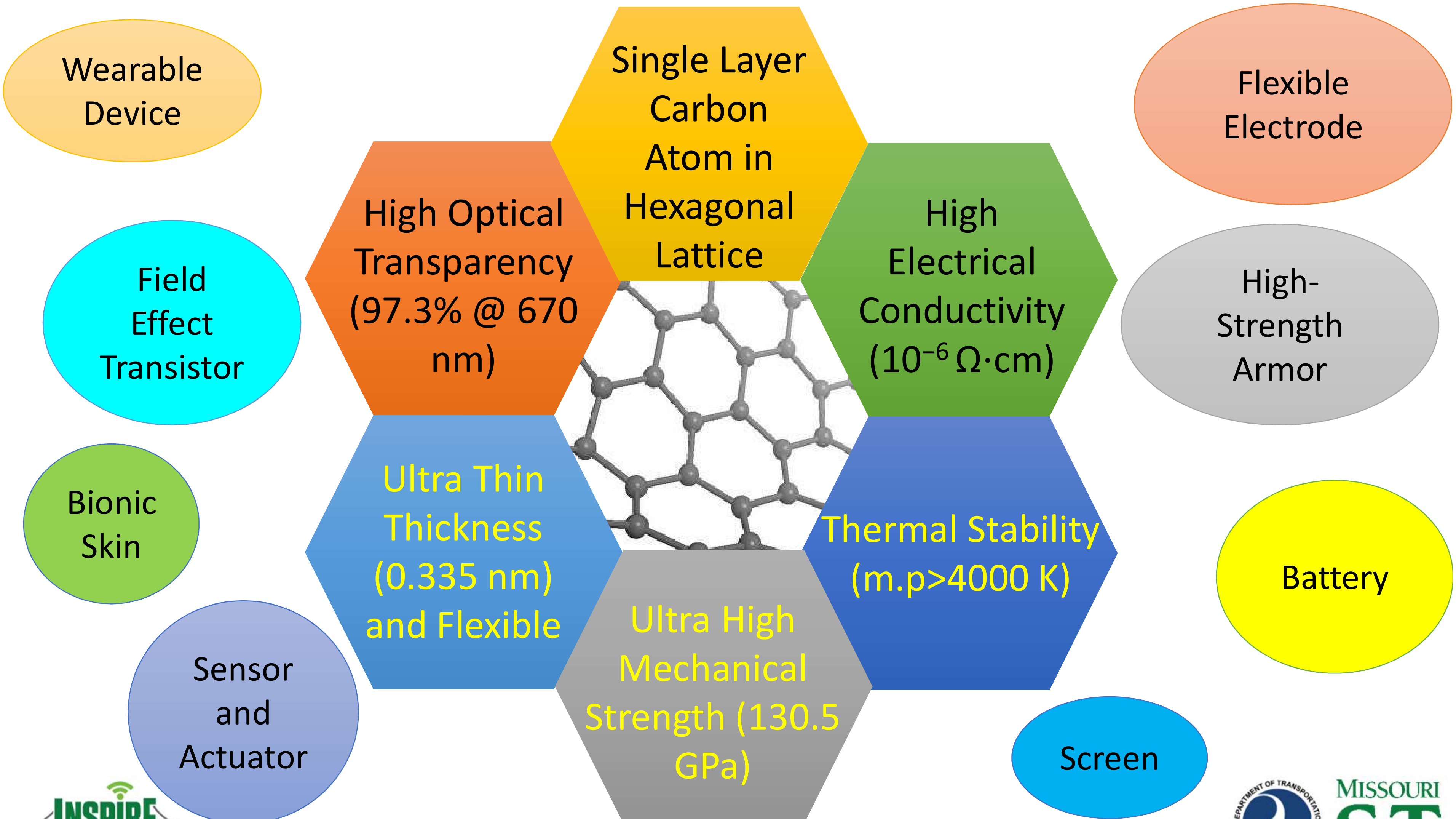
Fe-C coated LPFG for corrosion induced mass loss measurement

- Transparent Conductive Film – Graphene
  - Nobel Prize Winner material
- 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
  - Conductive
  - Optical transparent
  - 0.3 nm single layer thickness



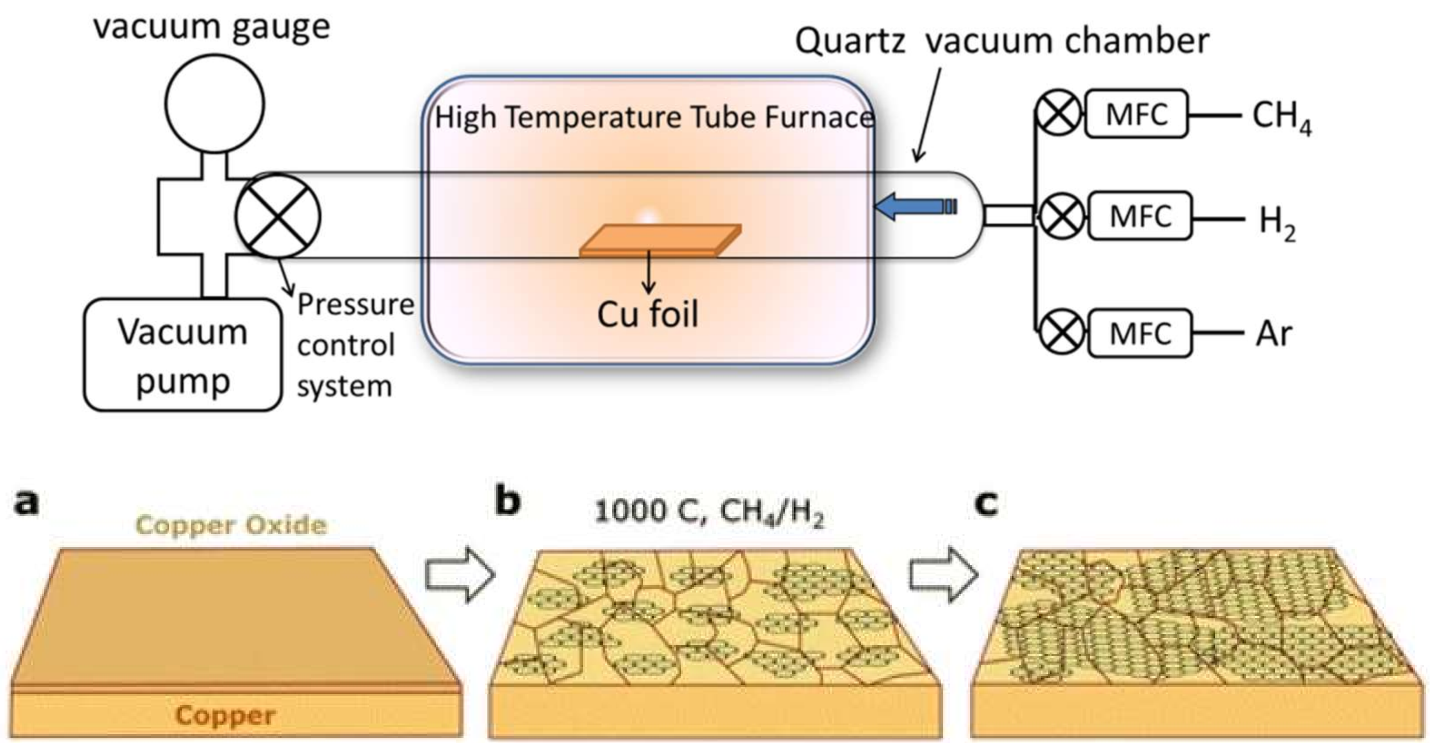
Fe-C coated LPFG for corrosion induced mass loss measurement

- **Graphene Properties and Applications**



Fe-C coated LPFG for corrosion induced mass loss measurement

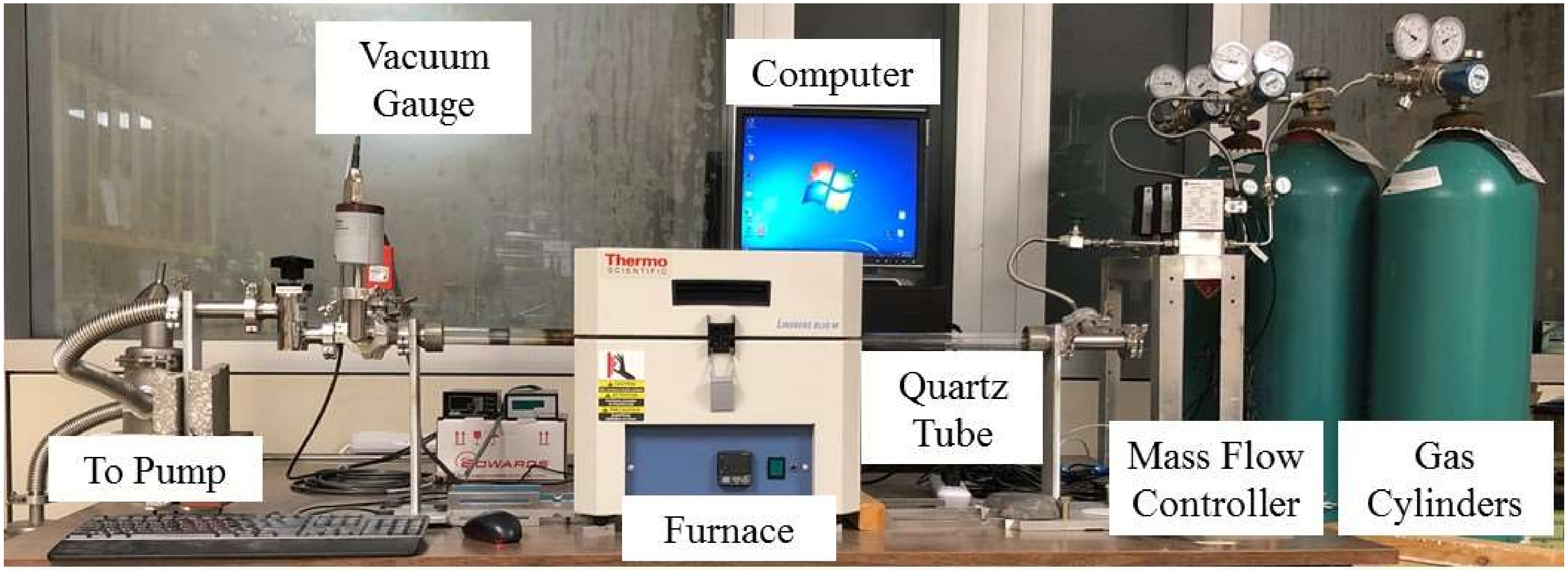
- **Graphene Synthesis through Low Pressure Chemical Vapor Deposition (LPCVD)**



Schematic illustration of graphene growth on copper via LPCVD

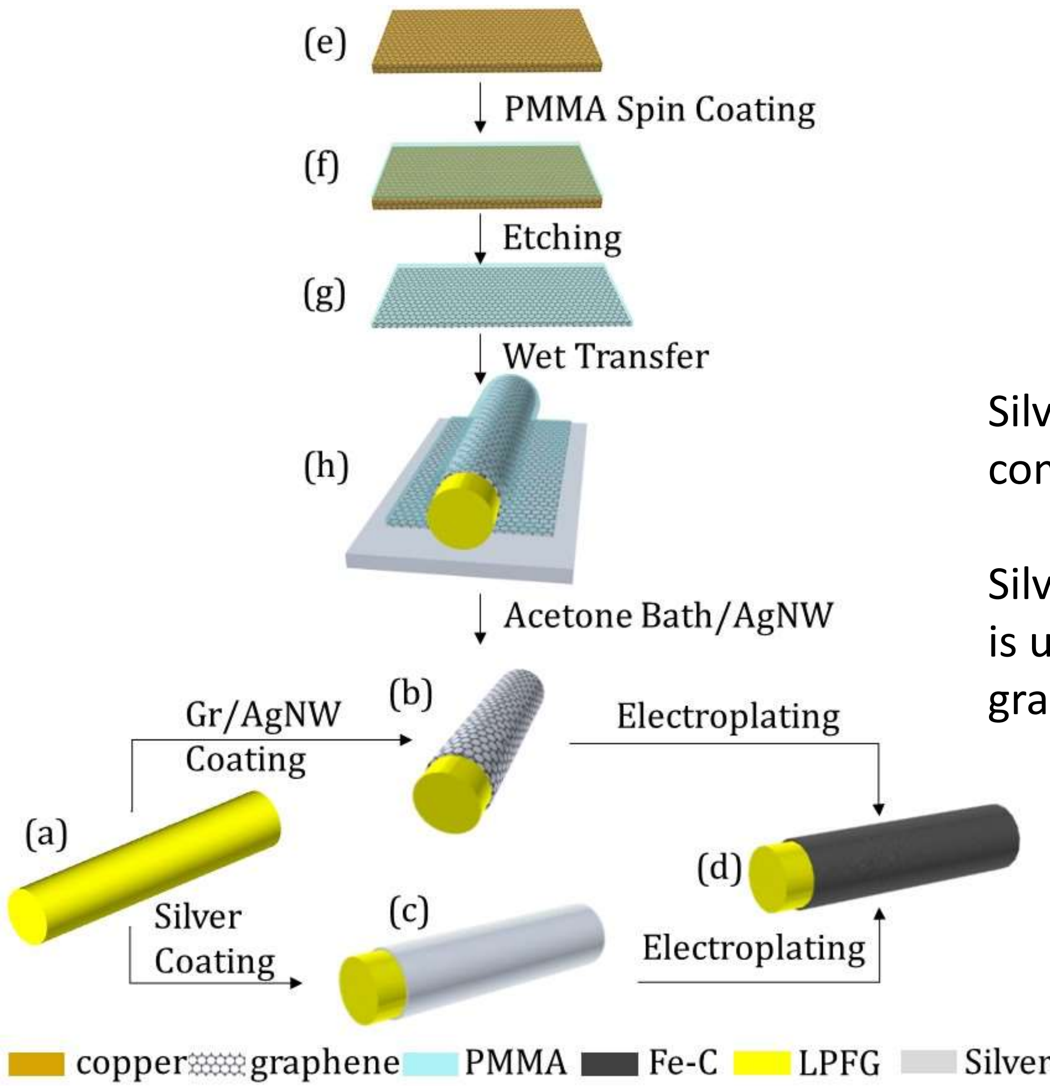
Fe-C coated LPFG for corrosion induced mass loss measurement

- LPCVD system in SPAR Lab



Fe-C coated LPFG for corrosion induced mass loss measurement

- **Fe-C coated LPFG Corrosion Sensor Fabrication**

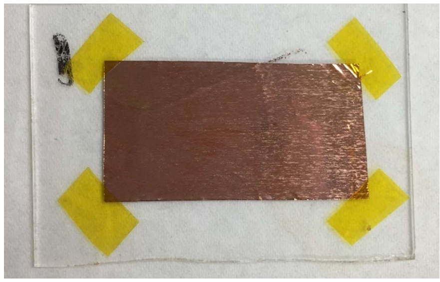


Silver layer is used for comparison

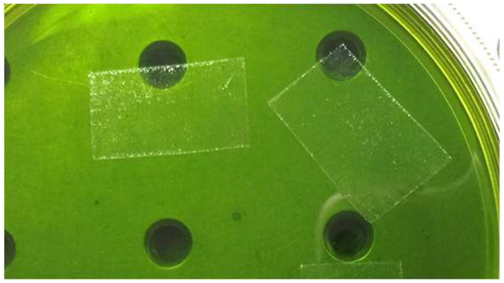
Silver nanowire (AgNW) is used to enhance the graphene conductivity

Fe-C coated LPFG for corrosion induced mass loss measurement

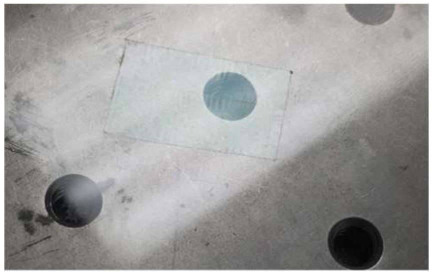
- **Fe-C coated LPFG Corrosion Sensor Fabrication**



As-grown Gr on copper with PMMA coating



PMMA/Gr after etching



PMMA/Gr on DI water

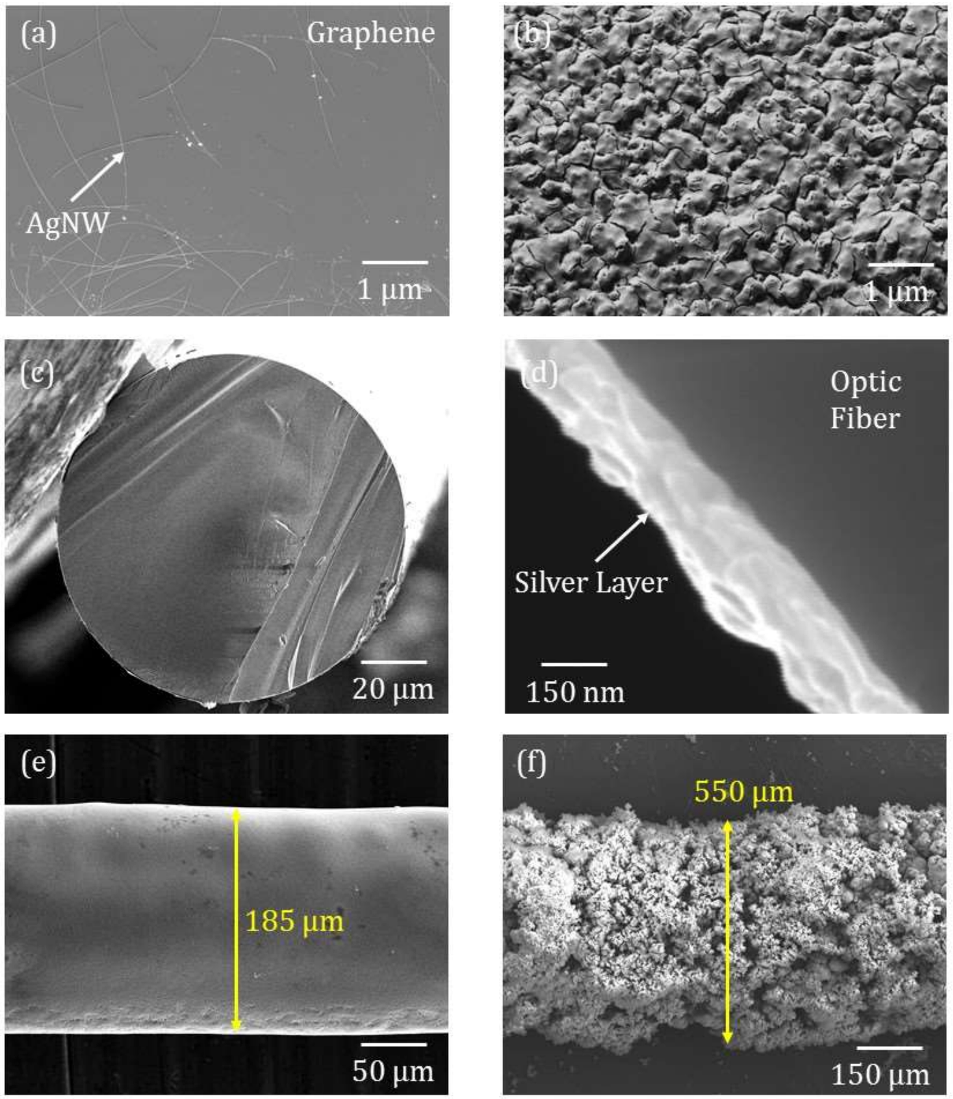
PMMA/Gr coated on LPFG

Electroplating

Fe-C coated LPFG

Fe-C coated LPFG for corrosion induced mass loss measurement

- **Characterization of the Coating Layer**



(a) Gr/AgNW composite

(b) Fe-C grains

(c) cross section of silver coated LPFG

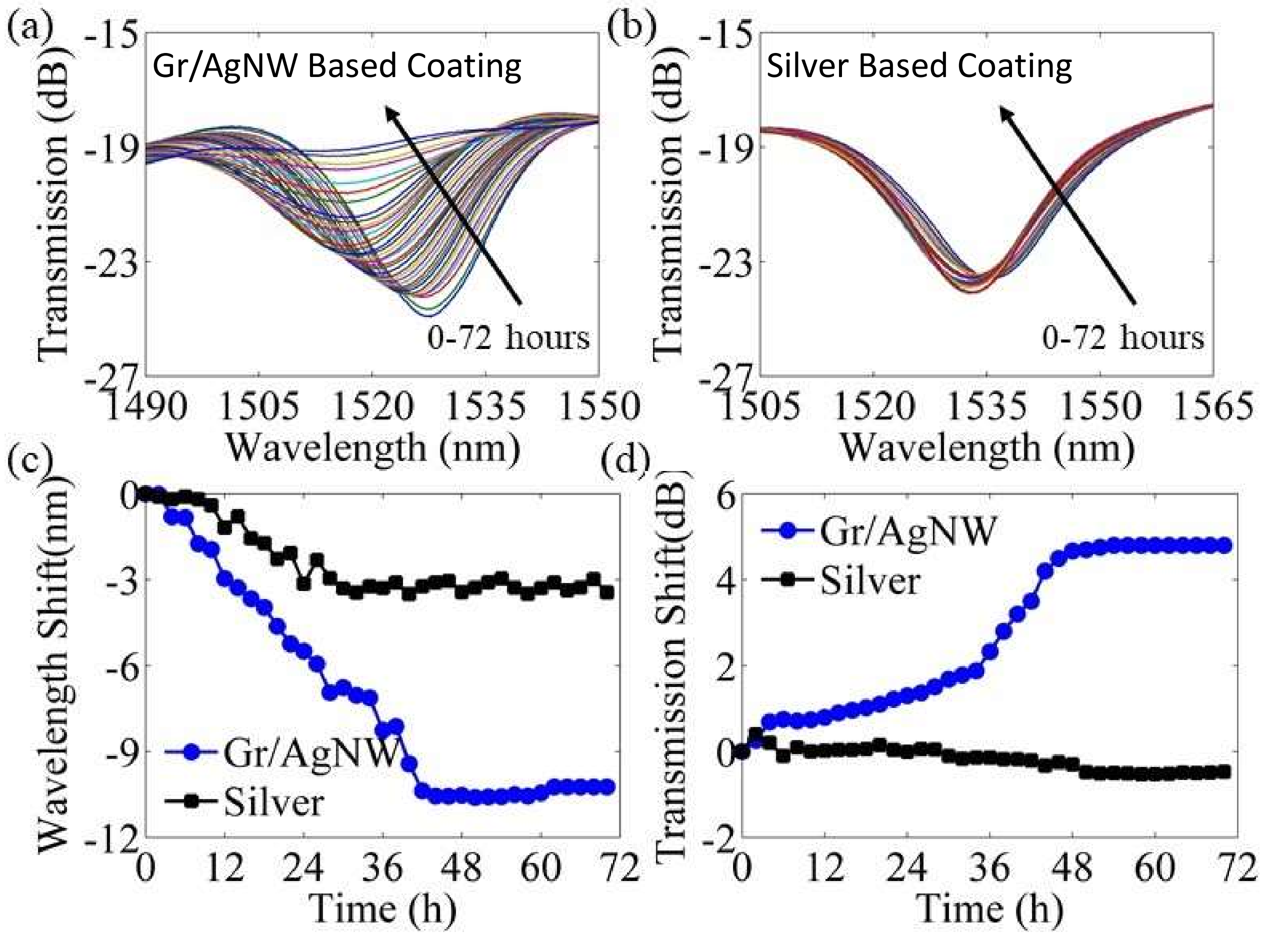
(d) thickness of silver layer

(e) Fe-C coated LPFG before and

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

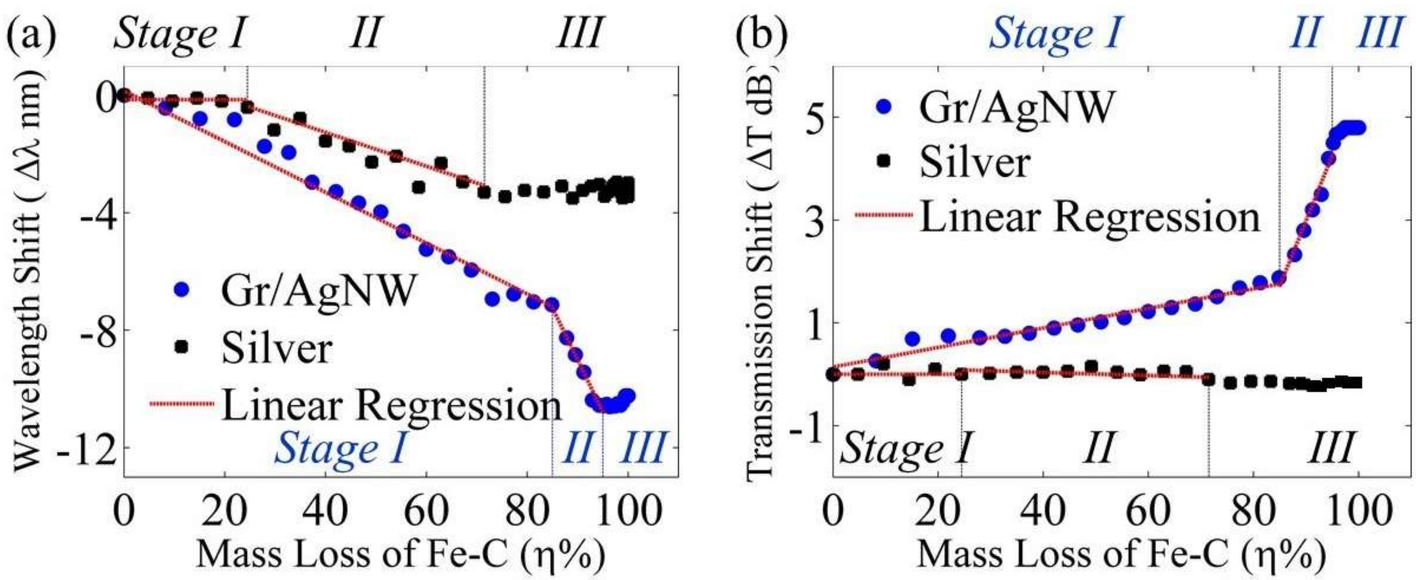
Fe-C coated LPFG for corrosion induced mass loss measurement

- **72 Hours Corrosion Test**



Fe-C coated LPFG for corrosion induced mass loss measurement

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



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

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

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

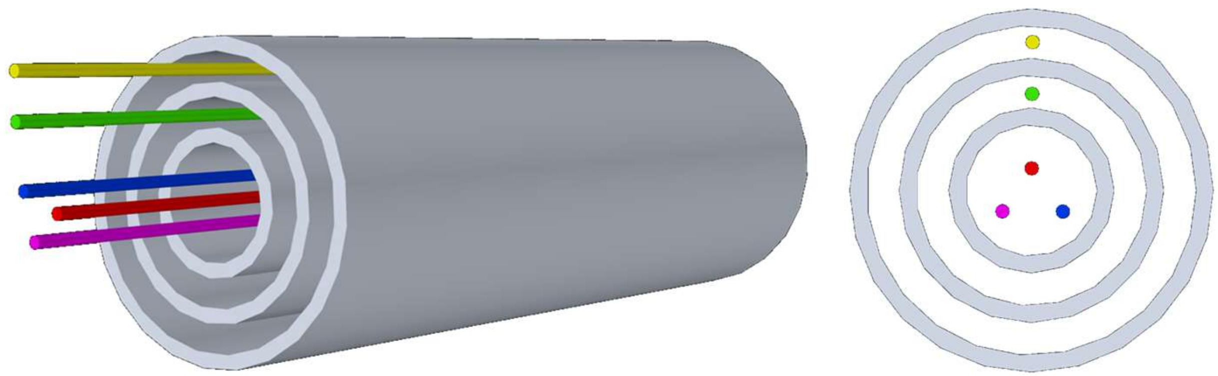
$\Delta T_{GI} = 0.019\eta + 0.14$ ($R^2 = 0.95$)

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

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

Integrated Sensor for Strain, Temperature and corrosion measurement

- **Sensor Design**



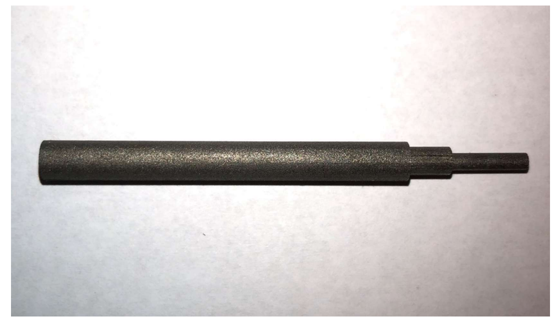
Steel tube extracted from steel members to be monitored for LPFG protection and monitoring of average corrosion

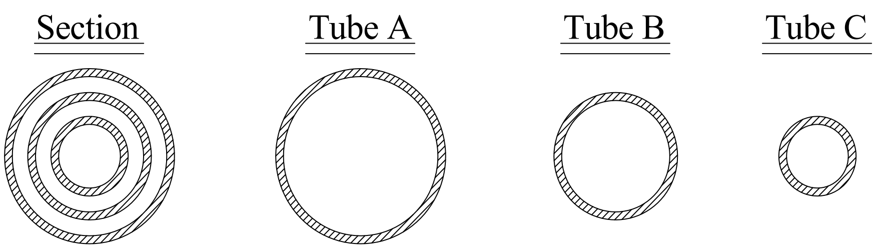
Three Fe-C coated LPFG sensors for the measurement of corrosion rate as each tube wall is completely penetrated.

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.

Integrated Sensor for Strain, Temperature and corrosion measurement

- **Sensor Design**





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

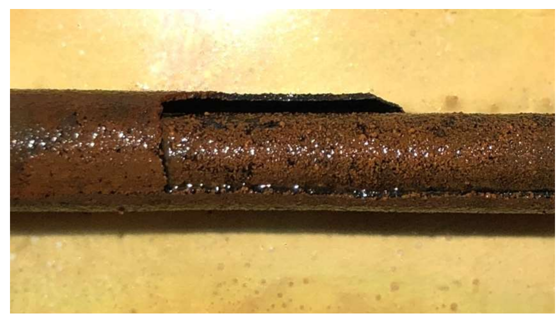
Integrated Sensor for Strain, Temperature and corrosion measurement

- **Strain and Temperature Monitoring**
  - **Similar to previous strain and temperature measurement**
- **Long-term Corrosion Monitoring**

Rebar before corrosion test

Single tube after penetration

Rebar after corrosion test



Double tube after penetration

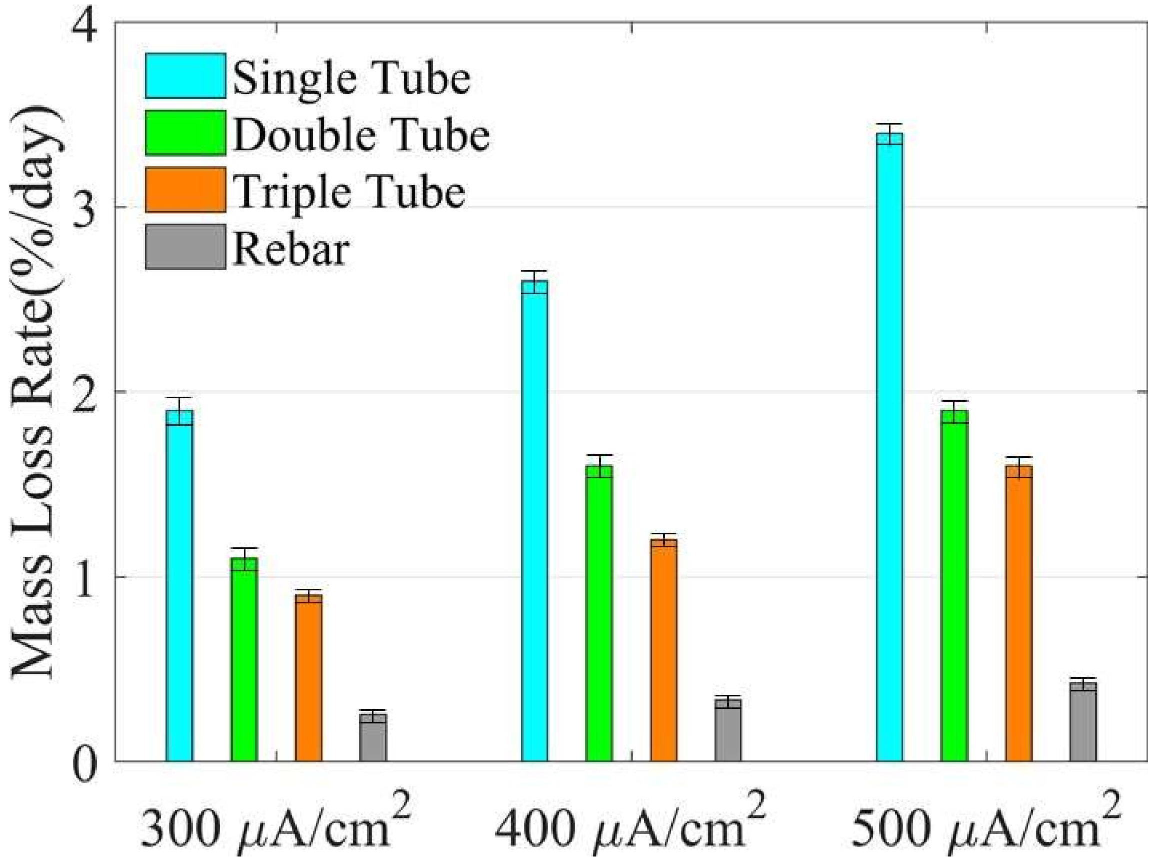
Integrated Sensor for Strain, Temperature and corrosion measurement

- **Corrosion Monitoring**
  - **Mass Loss Calibration**

Sample	Current Density ($\mu A/cm^2$)	Rebar Mass Loss Per Day (%)			Steel Tube Mass Loss Per Day (%)		
		5 cm	10 cm	15 cm	5 cm	10 cm	15 cm
Single Tube	300	0.24	0.26	0.26	1.9	2.1	1.9
	400	0.33	0.35	0.32	2.6	2.7	2.5
	500	0.43	0.44	0.41	3.3	3.4	3.5
Double Tubes	300	0.21	0.22	0.27	1.2	1.3	1.1
	400	0.35	0.37	0.39	1.5	1.6	1.7
	500	0.46	0.42	0.47	2.1	2.0	2.2
Triple Tubes	300	0.21	0.25	0.28	1.0	0.9	1.0
	400	0.30	0.37	0.35	1.3	1.3	1.2
	500	0.41	0.46	0.47	1.6	1.5	1.6

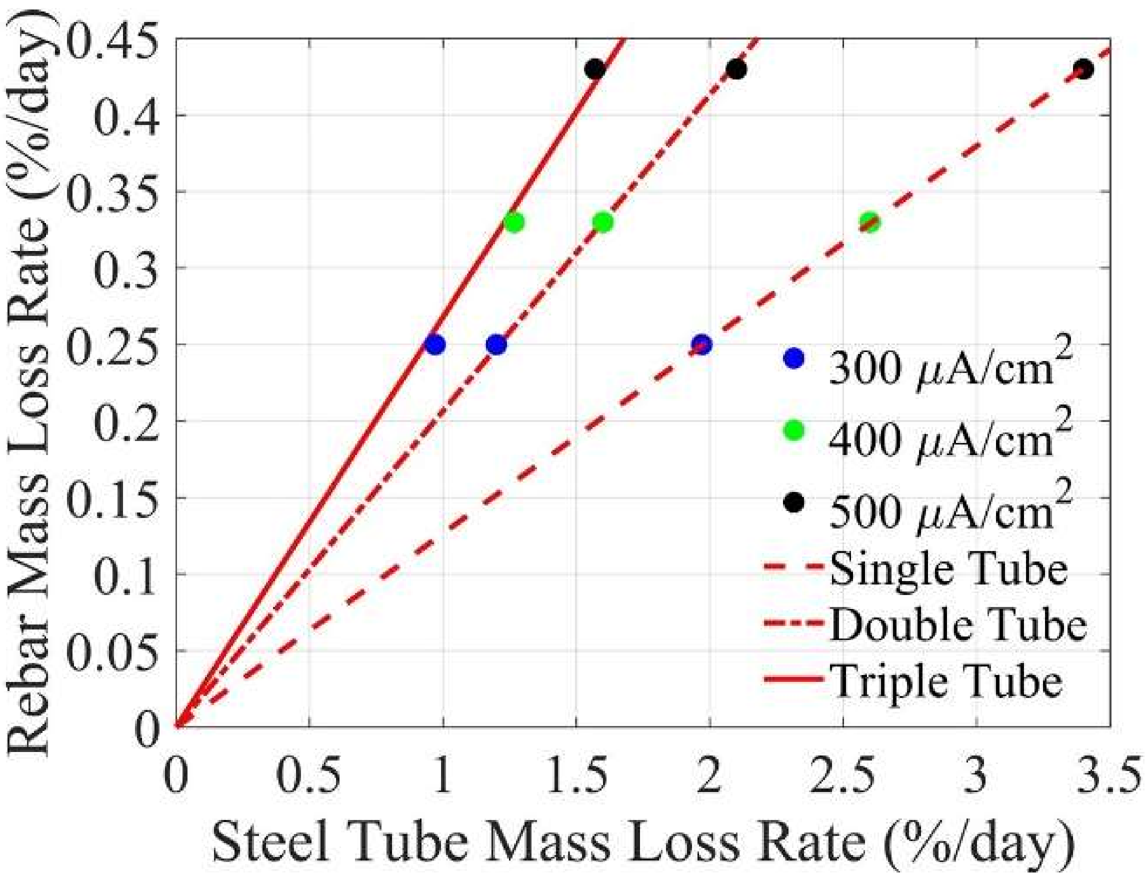
Integrated Sensor for Strain, Temperature and corrosion measurement

- **Corrosion Monitoring**
  - ➢ **Mass Loss Calibration**



Integrated Sensor for Strain, Temperature and corrosion measurement

- **Corrosion Monitoring**
  - **Mass Loss Calibration**



$$\beta_r = \frac{\beta_1}{7.91}, \quad R^2 = 0.99$$

$$\beta_r = \frac{\beta_2}{4.84}, \quad R^2 = 0.97$$

$$\beta_r = \frac{\beta_3}{3.73}, \quad R^2 = 0.93$$

β_r mass loss rate of rebar

β_1 mass loss rate of single tube

β_2 mass loss rate of double tube

β_3 mass loss rate of triple tube

Integrated Sensor for Strain, Temperature and corrosion measurement

- **Corrosion Monitoring**
  - **Penetration time of steel tube**

Sample	Penetration Time (Days)		
	300 µA/cm^2	400 µA/cm^2	500 µA/cm^2
Single Tube	12	9	7
Double Tubes	27	21	16
Triple Tubes	46	35	28

- The penetration time through the wall of tube(s) decreases with the increasing current density due to the accelerated mass loss rate.

- More number of tubes needs longer time for penetration.

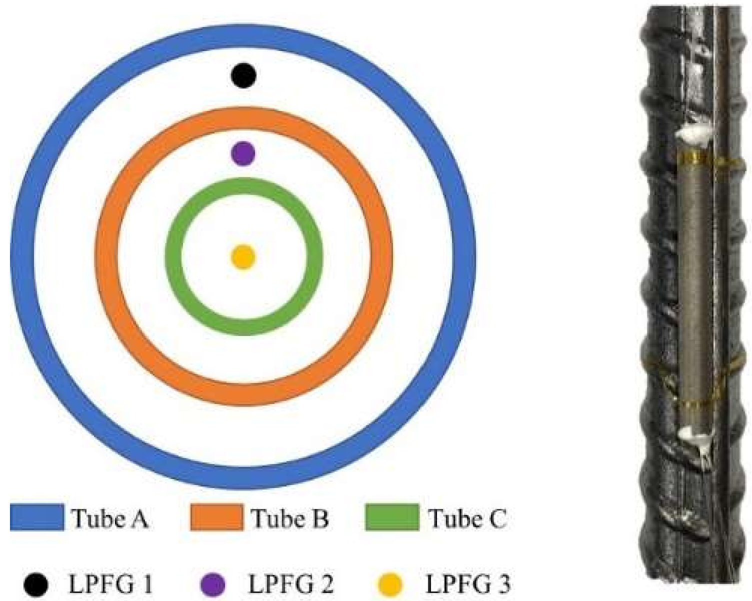
Integrated Sensor for Strain, Temperature and corrosion measurement

- **Corrosion Monitoring**
  - **Mass loss after penetration**

Sample	Current Density (μA/cm^2)	Steel Tube Measured Mass Loss (%)	Steel Tube Calculated Mass Loss (%)	Error	Rebar Measured Mass Loss (%)	Rebar Calculated Mass Loss (%)	Error
Single Tube	300	24.1	23.6	2.1%	3.2	3.0	6.3%
	400	24.5	23.4	4.5%	3.1	2.9	6.5%
	500	25.7	23.8	7.4%	2.8	3.0	7.1%
Double Tubes	300	35.1	32.4	7.7%	6.3	6.7	6.3%
	400	35.3	33.5	5.1%	6.5	7.0	7.7%
	500	32.4	33.6	3.7%	6.2	6.8	9.7%
Triple Tubes	300	46.5	44.5	4.3%	11.9	11.3	5.0%
	400	46.9	44.3	5.5%	12.4	11.7	5.6%
	500	42.1	43.9	4.3%	11.3	11.9	5.3%

Integrated Sensor for Strain, Temperature and corrosion measurement

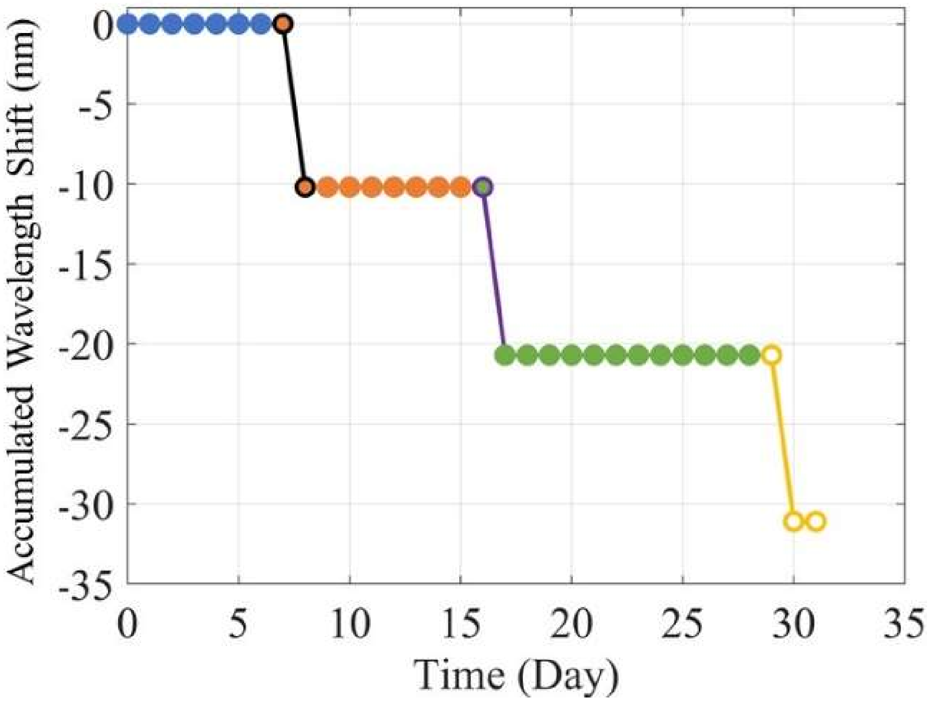
- Corrosion Monitoring
  - Accelerated corrosion test

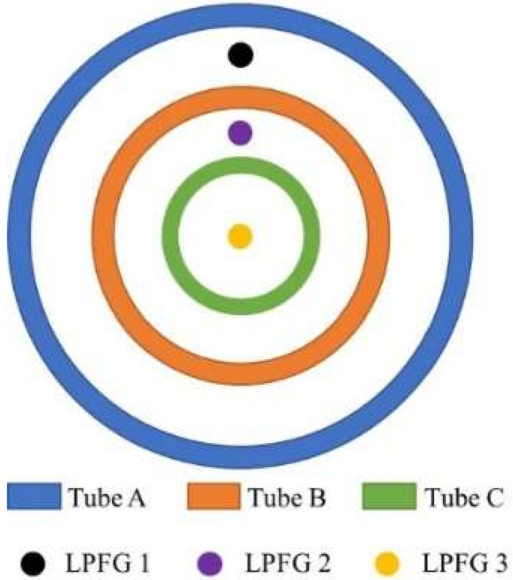


(a) (b)

Integrated Sensor for Strain, Temperature and corrosion measurement

- **Corrosion Monitoring**
  - **Constant current density 500 μA/cm²**



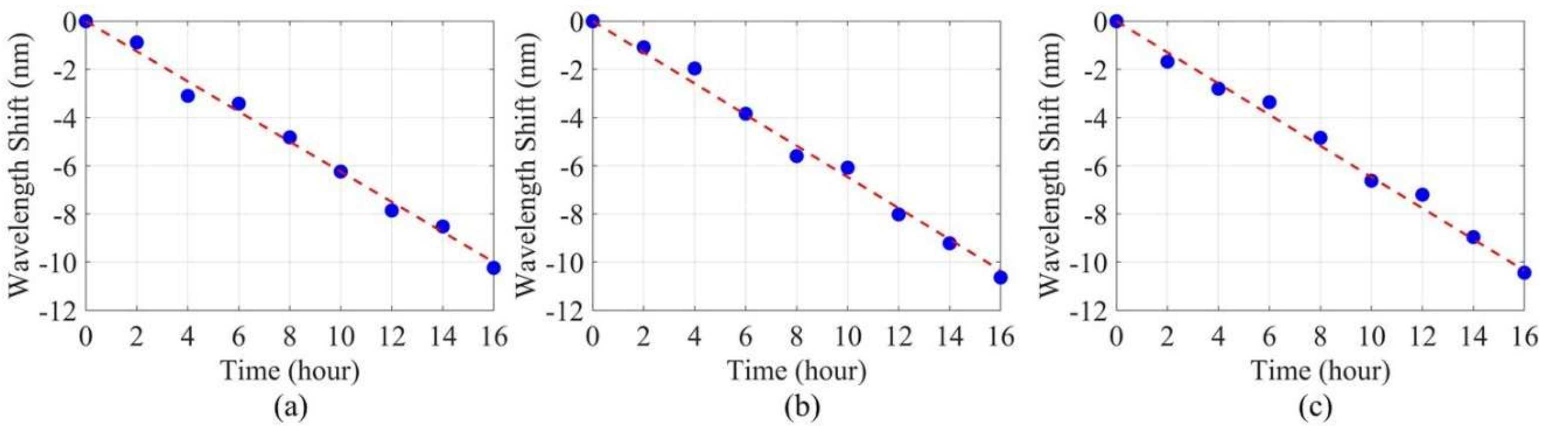


(a)

Integrated Sensor for Strain, Temperature and corrosion measurement

- **Constant current density**
  - **Rebar mass loss**

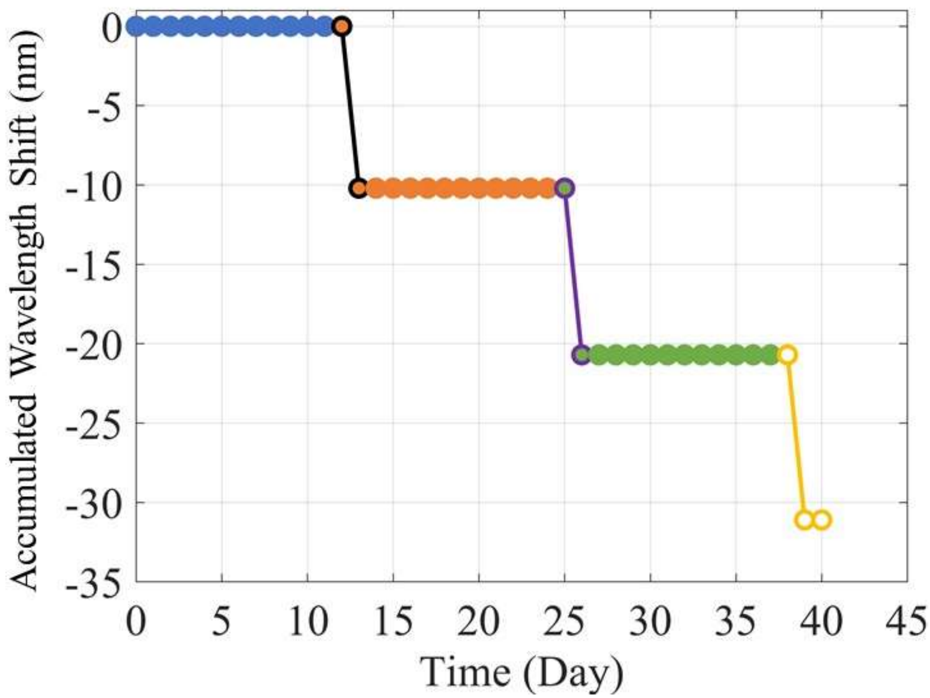
Penetration of Tube	Estimated Mass Loss Rate (%/day)	Measured Mass Loss Rate (%/day)	Error	Estimated Mass Loss (%)	Measured Mass Loss (%)	Error
Tube A	0.44	0.48	8.3%	3.1	3.4	8.8%
Tube B	0.43	0.46	6.5%	6.9	7.4	6.8%
Tube C	0.42	0.46	8.7%	12.2	13.3	8.3%

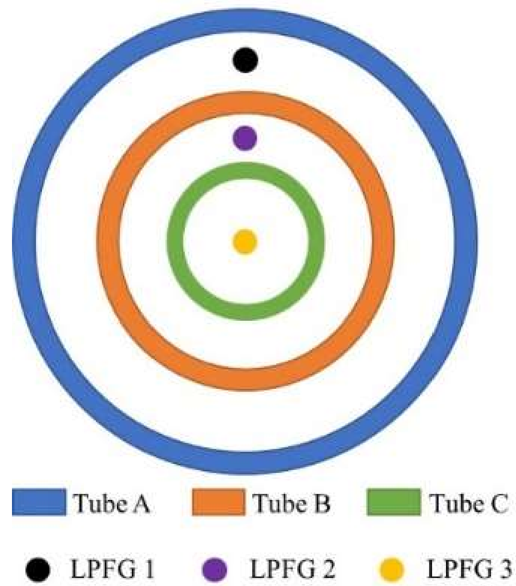


Resonant wavelength shifts over time of (a) LPFG 1, (b) LPFG 2 and (c) LPFG 3 sensors under a constant current density (500 μA/cm^2)

Integrated Sensor for Strain, Temperature and corrosion measurement

- **Corrosion Monitoring**
  - **Varying current density 300 – 400 - 500 μA/cm²**



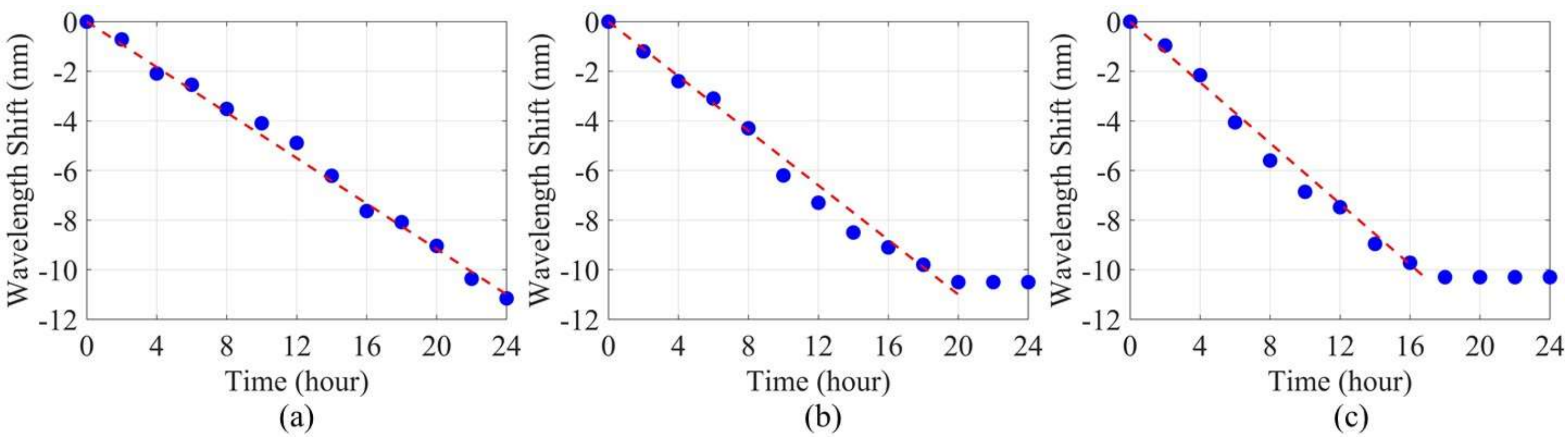


(a)

Integrated Sensor for Strain, Temperature and corrosion measurement

- **Varying current density**
  - **Rebar mass loss**

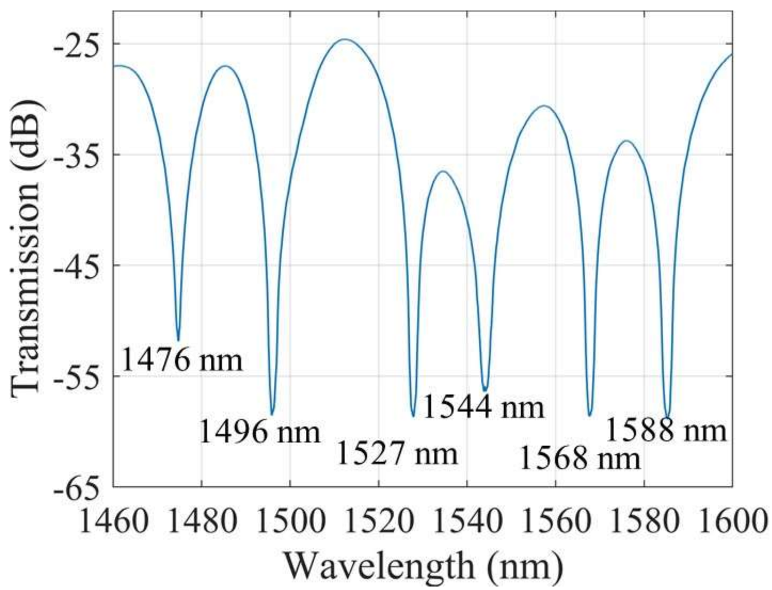
Penetration of Tube	Estimated Rebar Mass Loss (%)	Measured Rebar Mass Loss (%)	Error
Tube A	3.0	3.3	9.1%
Tube B	6.3	6.8	7.4%
Tube C	11.9	11.2	6.3%



Resonant wavelength shifts over time of (a) LPFG 1, (b) LPFG 2 and (c) LPFG 3 sensors under a varying current density

Maximum Numbers of LPFG Sensors for Multiplex sensing

- **Multiplex Sensing**
  - **Multiple LPFG sensors connected in one loop for multiplex sensing**



Transmission spectra of 6 LPFG sensors multiplexed in one fiber loop

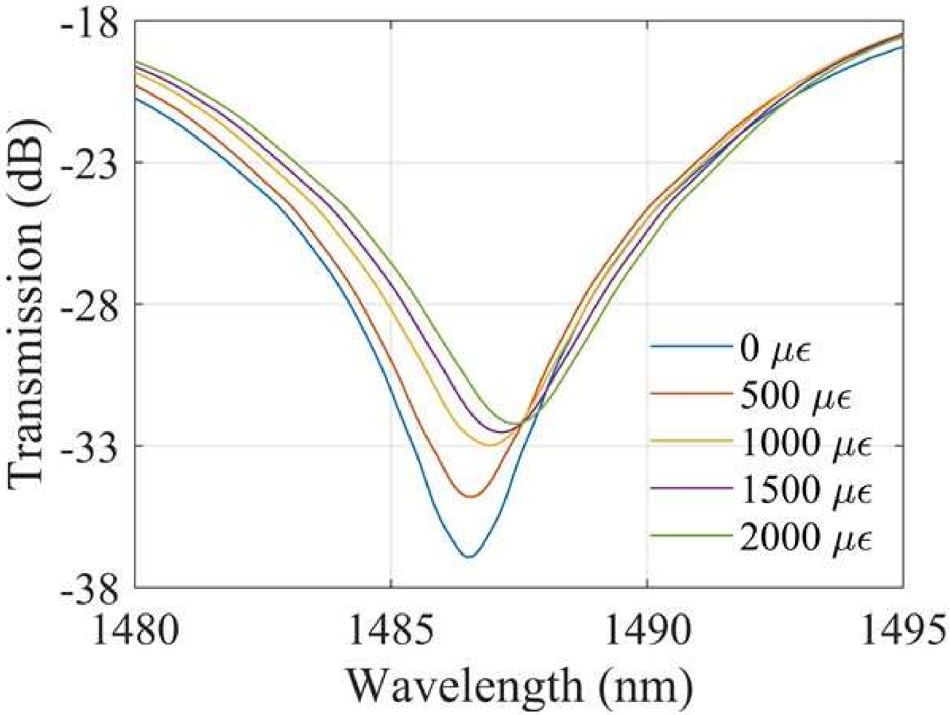
  - **Si255 has 16 channels (8 loops), so 6*8=48 LPFG sensors can be deployed at the same time for multiplexed sensing**

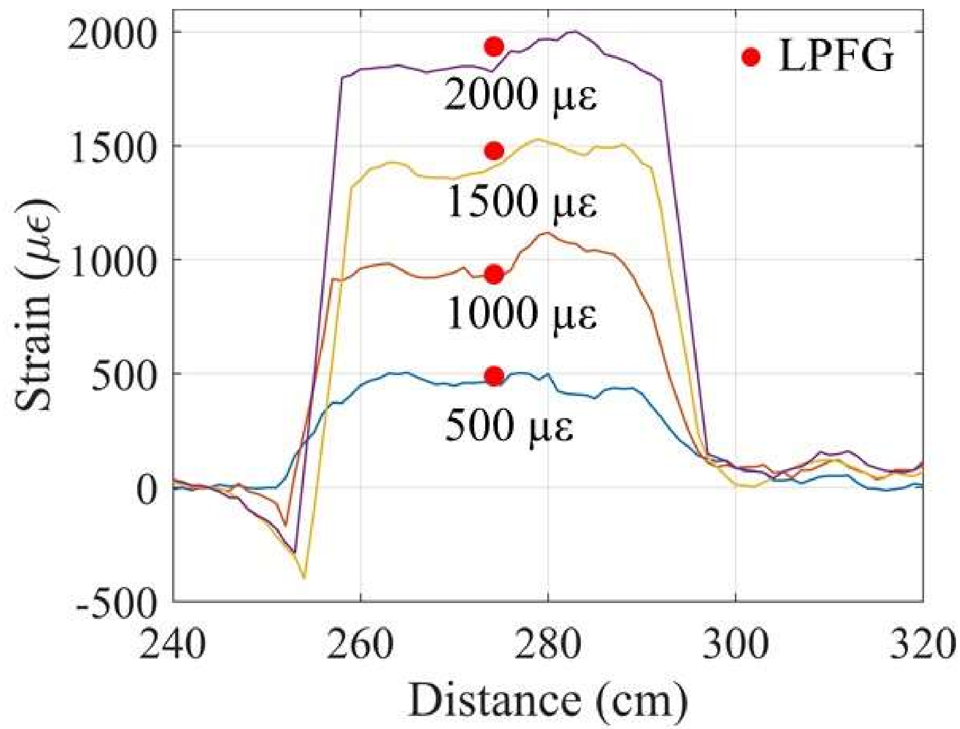
Interference between the LPFG and PPP-BOTDA

- Test setup

Interference between the LPFG and PPP-BOTDA

- **Test results**





- **There is no interference between LPFG and BOTDA**

Concluding Remarks

- The CO_2 laser grating system can fabricate the LPFG sensor, which can be used for strain, temperature and refractive index sensing.
- As-grown monolayer graphene can be synthesized on a copper foil using the LPCVD system. 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.
- 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.

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