CAAP Quarterly Report

Date of Report: *December 31, 2020*

Contract Number: 693JK31850012CAAP

Prepared for: *USDOT Pipeline and Hazardous Materials Safety Administration (PHMSA)*

Project Title: *Magnet-assisted Fiber Optic Sensing for Internal and External Corrosion-induced Mass losses of Metal Pipelines under Operation Conditions*

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For quarterly period ending: *December 31, 2020*

Business and Activity Section

(a) General Commitments – Dr. Genda Chen directed the entire project and coordinated various project activities.

Mr. Ying Zhuo, Ph.D. candidate in civil engineering at Missouri S&T, was on board for this project. He is responsible for the fabrication and characterization test of sensors under Dr. Chen's supervision.

(b) Status Update of Past Quarter Activities – Detailed updates are provided below by task.

Task 1 Optimization of a magnet-assisted hybrid FBG/EFPI sensor enclosed in a plexiglass container for simultaneous measurement of temperature and pipe wall thickness

Task 1 was completed in the fourth quarter of 2019.

Task 2 Development and validation of a graphene-based LPFG sensor with Fe-C coating for improved sensitivity in mass loss measurement in varying temperature environment

In the last quarter, we proposed a new experimental design to solve the problem of the accumulated inelastic deformation on the optical fiber. However, only one long period fiber gratings (LPFG) sensor was tested successfully. To increase the reliability of the experimental results, three LPFG sensors were fabricated and tested in this quarter. Transmission spectra of a typical LPFG sensor (no. 8 as designated later) was presented in Fig. 1. In general, the resonant wavelength shifts downward. The resonant wavelength shifts of the LPFG sensors (no.7-9) coated with a varying number of graphene (Gr) layers were summarized in Table 1 and presented in Fig. 2. It can be observed from Fig. 2 that the wavelength shift of LPFG sensors decreased with the increase in number of graphene layers until the number of Gr layers reached 9 or 12. With a further increasing number of Gr layers, the wavelength shift of sensors appears to be fluctuated, an indication of saturation.

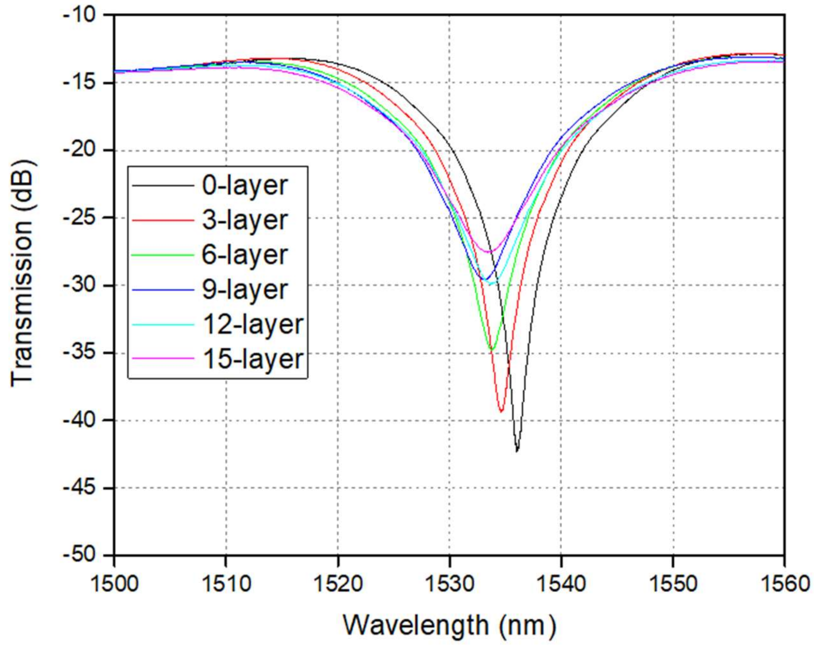

Fig. 1 Transmission spectra of a typical LPFG sensor (no.8) coated with a varying number of graphene layers

Table 1 Resonant wavelength shifts of LPFG sensors (no.7-9)

Number of graphene layers	Wavelength Shift(nm)		
	Sensor 7	Sensor 8	Sensor 9
0	0	0	0
3	-2.672	-1.408	-1.648
6	-2.408	-2.216	-3.120
9	-3.184	-2.880	-4.144
12	-3.488	-2.368	-3.104
15	/	-2.608	-4.264

Note: Sensor 7 was broken when coated with the 15^{th} Gr layer.

To get a quantitative conclusion between the wavelength shift and the Gr layers, we considered no. 2, 4, 7, 8, 9 sensors for further analysis since their sample preparation and test procedure were more consistent. These five sensors were renamed as EF1-EF5 (EF means Evanescent Field) and their test results were shown in Fig 3. According to our previous reports, the wavelength shift would decrease with the increase of Gr layer number until the number of Gr layers reached 12. As such, the data with 15-layer Gr were neglected in the following analysis. A few abnormal points were marked with red circles in Fig. 3 likely due to the variation of manual preparation of these sensors. Those abnormal points were also neglected for they were far beyond the reasonable range. Based on the remaining data, two regression lines were determined: linear and exponential, both starting at the origin (0, 0) since no wavelength shift exists when sensors have not been coated with Gr (a reference itself). The least-square approach was used to get the linear and nonlinear regression lines. Theoretically, the penetration depth of the evanescent field surrounding an optical fiber decays exponentially with the distance in radial direction, so exponential regression was considered. The regression results of two methods were shown in Fig. 4.

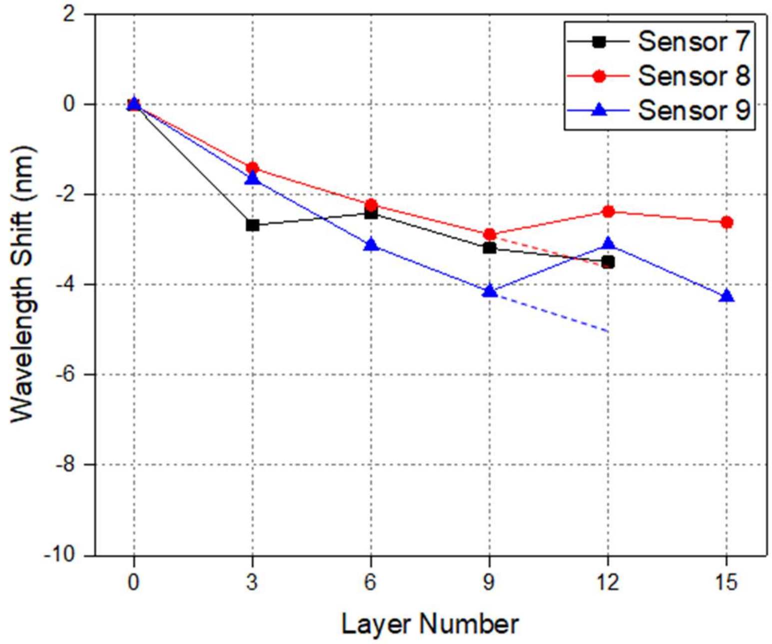

Fig. 2 Wavelength shifts of the LPFG sensors (no.7-9) with a varying number of graphene layers

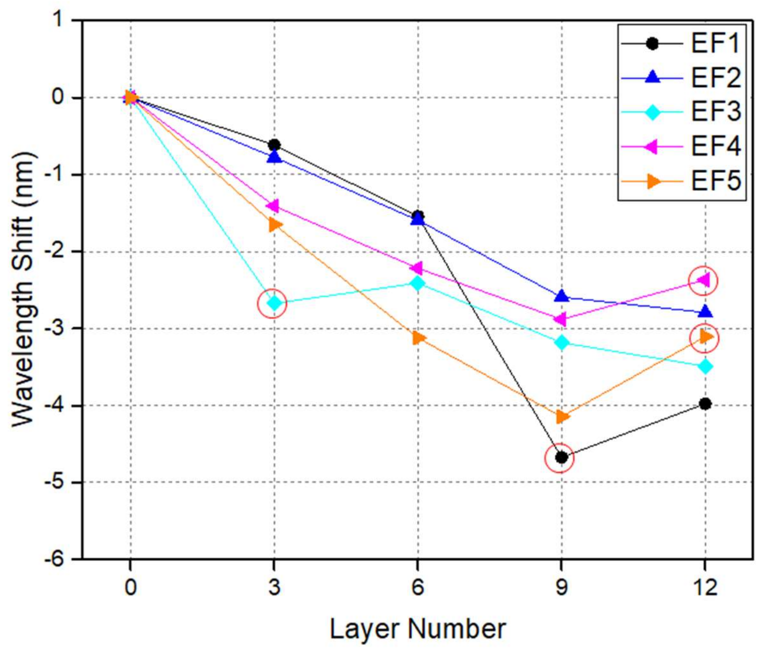

Fig. 3 Wavelength shifts of all effective LPFG sensors with a varying number of graphene layers

The linear and exponential regression equations are shown below,

$$\Delta\lambda = -0.326\, n \tag{1}$$

$$\Delta\lambda = 5.855(e^{-0.079n}-1) \tag{2}$$

where $\Delta\lambda$ is the wavelength shift (nm), and n is the number of the coated graphene layer. The coefficients of determination (COD, denoted as R^2) for Eq. (1) and Eq. (2) are 0.94 and 0.87, respectively. The closer the value of COD is to 1, the better the fit between data and regression equations. Both methods seemed to give a good fit.

The regression equations provide quantitative description for the evanescent field attenuation in radial direction of optical fibers. It can be known from Eq. (1) that the wavelength shift decreases 0.326 nm for every coated Gr layer, and the wavelength shift will achieve the lowest value, which is -3.912 nm, when the number of the coated Gr layer is 12. From Eq. (2), the wavelength shift decreases exponentially and achieves the lowest value with the 12-layer coated Gr, which is -3.586 nm. Though the two methods have different lowest values, their change trends are similar. The linear regression represented by Eq. (1) is much simpler in computation. The exponential regression in the form of Eq. (2) is more insightful to the theoretical explanation, which could be used for in-depth analysis of the evanescent field surrounding a LPFG sensor.

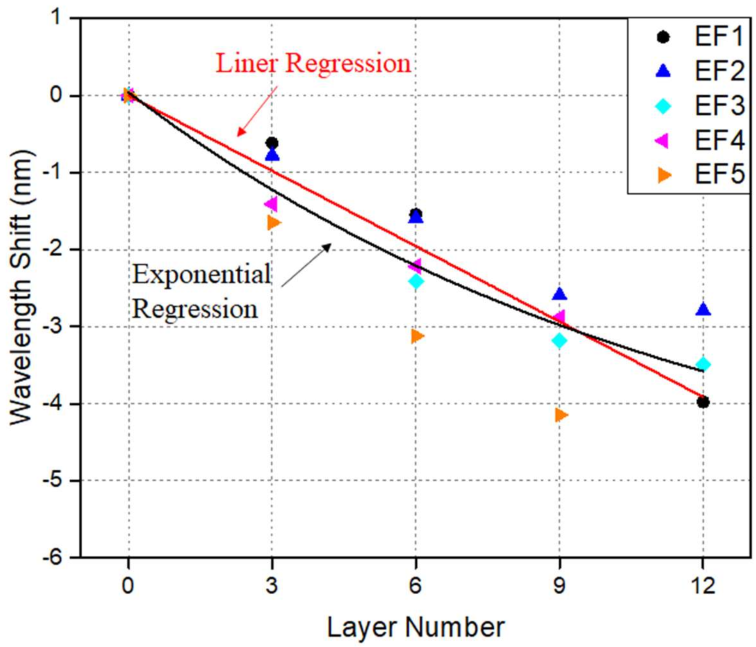

Fig. 4 Regression analysis result between wavelength shift and Gr layer number

(c) Planned Activities for the Next Quarter - The following activities in Task 2 and Task 3 will be executed during the next reporting quarter.

Task 2 Development and validation of a graphene-based LPFG sensor with Fe-C coating for improved sensitivity in mass loss measurement in varying temperature environment

After the study on evanescent field attenuation has been completed in this quarter, we will begin to investigate and report the effect of operation temperature on corrosion process and thus mass loss during the next quarter.

Task 3 Integration and field validation of multiple FBG/EFPI and multiplexed LPFG sensors for internal and external corrosion monitoring of a pipeline with temperature compensation.

The creep effect will be researched to get meaningful results.

(d) Problems Encountered during this Quarter and Potential Impact on Next Quarter – This project continues to be impacted by COVID-19. To keep six feet apart between any two students in laboratory, limited laboratory access is available to students. As such, students sometimes have to work in shift.