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Methodology to Account for Radiation and Temperature Influences on Optical Fibers compaction and Index of Refraction

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ABSTRACT

The effects of radiation induced compaction and index of refraction change can cause significant drift in the measurements from intrinsic fiber optic temperature sensors. The work presented here aims to develop and test a methodology to measure these macroscopic properties that are responsible for the drift in order to correct the measurement. This report discusses the measurement methodology, theory, and sensor construction. Preliminary results from the first irradiation test using this sensor are provided here.

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ACRONYMS

IR	Infrared
RIA	Radiation-induced Attenuation
RIE	Radiation-induced Emission

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Introduction and Motivation

Significant research has been conducted over the past several years to develop fiber optic sensors capable of operating in high radiation environments. This has included research identifying optical fibers which can withstand high radiation environments and how to mitigate the sensor drift exposed in these environments. This research has improved the ability to measure multi-point or distributed temperature measurements in high radiation environments. The radiation induced attenuation challenges have largely been mitigated for most sensor applications under low dose conditions using pure silica core, F-doped cladding optical fiber. Fibers of this construction are commercially available and have shown good resistance to radiation induced attenuation. However, under high dose conditions significant sensor drift is observed yielding these sensors useless. This problem is unique to intrinsic fiber optic sensors because they rely directly on the optical behavior of the fiber. Whereas extrinsic optical fiber sensors only utilize the fiber to transmit the light from the sensor to the light analysis device.

Intrinsic fiber optic sensors all function similarly in that the parameter of interest alters the optical properties of the fiber. This is typically achieved through length and index of refraction changes. The measurement of these changes varies based on the specific sensor, but all of them are based on this same concept. The three most common intrinsic sensing mechanisms are Rayleigh backscatter, Fiber Bragg Gratings (FBGs), and Fabry-Perot cavities. The distributed Rayleigh backscatter sensing relies on random changes of the index of refraction along the length of the fiber. The FBGs rely on a modulation of index of refraction (grating) in the fiber to reflect light at a specific wavelength. This wavelength changes as the index of refraction changes with temperature and the period between the index of refraction modulation changes with thermal expansion. With Fabry Perot cavities the optical distance between two partial reflectors changes with both the thermal expansion and the index of refraction changes with temperature. This results in an interference pattern that is dependent on both of these factors. It is clear from the operation of these sensors that the thermal behavior of these sensors is entirely comprised of the dimensional and index of refraction changes of the sensors.

Optical fibers are a unique classification of sensors because they can be used as both multi-point sensors, but also multi-parameter sensors. Wave division multiplexing has become commonplace in most fiber optic applications to push more information through the fibers. This concept has largely been used to increase the number of sensing points or sense multiple variables for nuclear applications. The active compensation work that is being reported here has been working to measure the changes in macroscopic properties that are responsible for the drift of these sensors. By using these measured values in real-time to account for the sensor drift these changes are imposing. Specifically, the radiation induced compaction and index of refraction changes. The progress made in the development of this strategy is the focus of this report.

Theory

The index of refraction and any length changes resulting from radiation are needed to account for the resulting drift in the fiber optic sensors. Specifically, it is well known that radiation will compact the optical fibers and change the index of refraction. It is known the radiation can impact index of refraction through the Kramers-Kronig relations by the radiation induced attenuation. Additionally, the radiation induced compaction will induce an index of refraction change through the Lorentz-Lorenz relationship, however, these two mechanisms are likely not the only two responsible for index of refraction changes in the optical fiber. No understanding of the mechanistic behavior of the index of refraction (or compaction) changes is actually required for the compensation of the drift due to these changes. However, measuring these changes under known conditions may lead to a better understanding of the mechanisms responsible for these changes.

The use of cascaded Fabry Perot cavities has been proposed as a means to measure index of refraction changes and length changes from radiation. The two cascaded cavities are made entirely of silica with the first one utilizing silica capillary tube and the second made with a coreless fiber as shown in Figure 1. The light propagates into the air cavity inside the capillary tube creating interference between reflections from surface 1 and 2. The light transmitted through the first cavity also interferes with itself between the reflection from 2 and 3. The final interference is obtained between the reflections at surface 1 and surface 3.

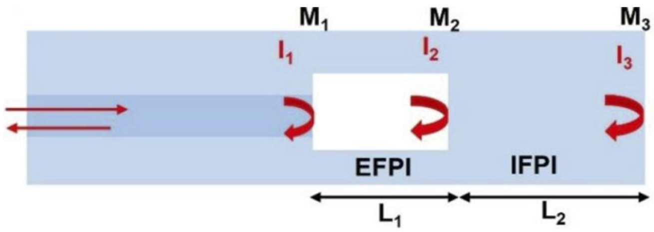

Figure 1 Diagram of structure to use for active compensation of radiation effects on optical fibers

The reflected intensity of light is given by

$$I = I_1 + I_2 + I_3 + 2\sqrt{I_1 I_2}\cos(\phi_{air}) + 2\sqrt{I_2 I_3}\cos(\phi_{silica}) + 2\sqrt{I_1 I_3}\cos(\phi_{air-silica})$$

where $\phi_{air} = \frac{4\pi n_1 L_1}{\lambda}$, $\phi_{silica} = \frac{4\pi n_2 L_2}{\lambda}$, $\phi_{air-silica} = \frac{4\pi}{\lambda}(n_1 L_1 + n_2 L_2)$ are the phase shift of the air cavity, silica cavity and hybrid cavity. Interference of these cavity is plotted in Figure 2a, and the associated Fourier transform of the data in Figure 2b. The location of peaks from a Fabry Perot cavity are used to determine the optical path length, which consists of the product of index of refraction and cavity length. This is typically done through by the use of the following equation

$$L = \frac{\lambda_1 \lambda_2}{2n(\lambda_2 - \lambda_1)}$$

where λ_1 and λ_2 are the wavelengths of two adjacent peaks and n is the index of refraction of the cavity. The peaks of each of the cavities cannot be easily identified in the combined signal shown in Figure 2a thereby requiring more involved data processing. The Fourier transform is first conducted to identify frequencies corresponding to the interference pattern. Then digital filtering is conducted at these frequencies to filter out the contribution of the other cavities. After obtaining the reconstructed signal after the filter, the peaks can be identified and cavity lengths calculated as is done traditionally with single cavity Fabry Perot sensors.

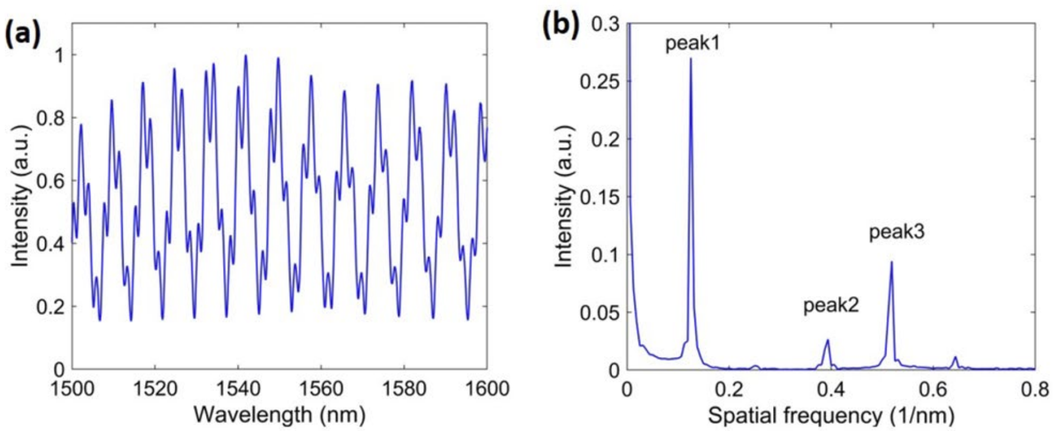

Figure 2 (a) Plot of the spectrum collected from interrogating the cascaded fabry perot sensors. (b) Plot of the amplitudes from the fast fourier transform from the spectra.

The index of refraction of the air cavity is not impacted by radiation, therefore, changes of the optical path length associated with this cavity are only result of the dimensional changes of cavity. It is assumed the air cavity and the silica cavity experience the same radiation induced compaction and therefore length contraction is the same. The interference pattern from the silica cavity is dependent on both the change of index of refraction and the length of the cavity. The length of the silica cavity can be calculated by multiplying the compaction observed in the air cavity to the original length of the silica cavity.

Results & Ongoing Experiments

The active compensation sensor is being tested in the Massachusetts Institute of Technology Reactor (MITR) and the Belgium Reactor 2 (BR2). The MITR irradiation has completed and the data analysis is ongoing. A brief overview of this data is covered in this report. The irradiation in BR2 is in collaboration with French Alternative Energies and Atomic Energy Commission (CEA). This sensor irradiation is scheduled to irradiated early in 2024.

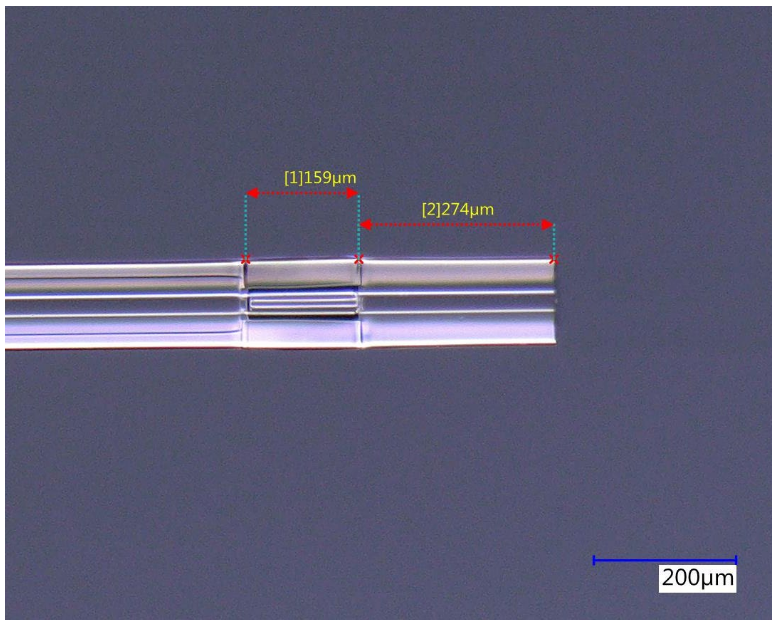

Figure 3 Microscope image of the active compensation sensor tested in this report

A microscope image from the active compensation sensor that was irradiated in the MITR can be seen in Figure 3. Both cavities of the Fabry Perot sensor can clearly be seen with rough measurement from the microscope image for each of them. A spectrum obtained from the MITR experiment is included in Figure 4 along with the Fourier transform of the same spectra. The contribution from each cavity can be seen clearly in both the interference spectrum and the Fourier transform. The three frequency peaks identified in the Fourier transform are used to apply bandpass filters at the original spectrum at the corresponding frequency. The results from filtering at the first two frequencies are presented in Figure 5. Using these plots the lengths of the air and silica cavities have been extracted. For each spectra collected, these plots are generated and the cavity lengths are extracted. The plots provided here are generally representative of the data collected in this experiment.

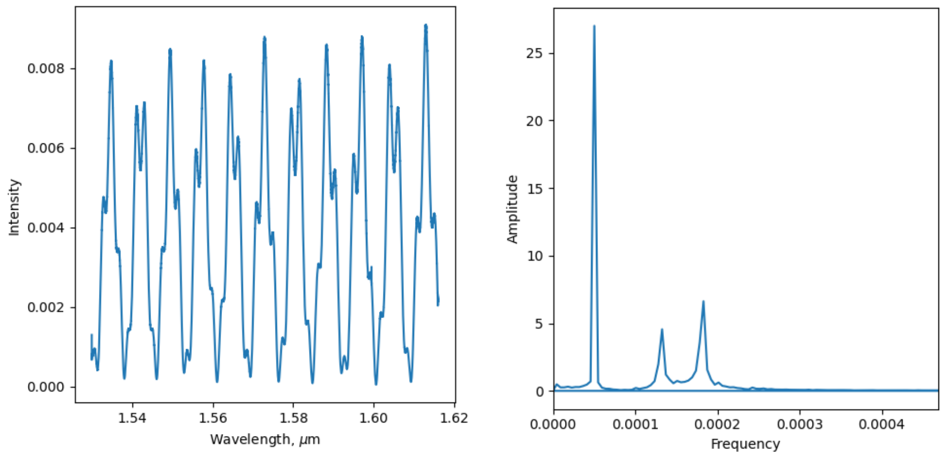

Figure 4 Spectrum (Left) collected from the active compensation sensor in the MITR experiment and it's Fast Fourier transform (Right)

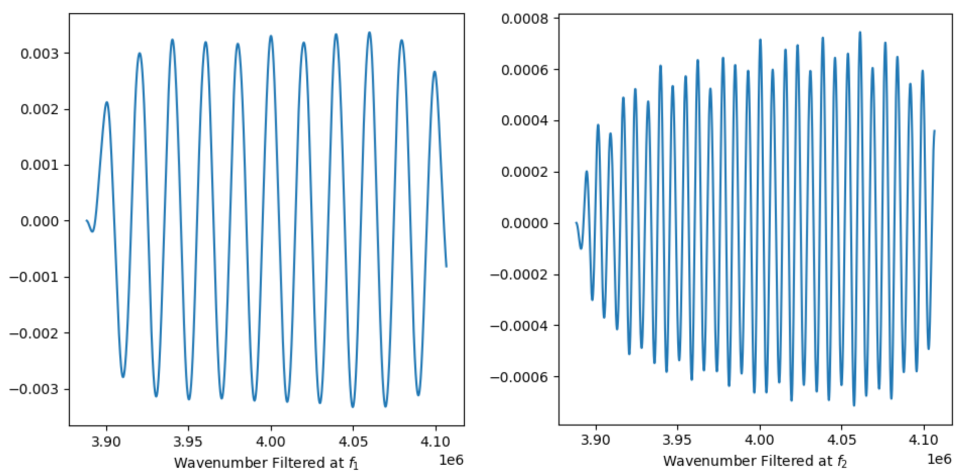

Figure 5 Plots of the intensity vs wavenumber after applying bandpass filters at f_1 (left) and f_2 (right) determined by the fast Fourier transform results.

The measured cavity lengths, reactor power, and irradiation temperature is provided in Figure 6 near the time of reactor startup. As the reactor starts up the effects from the temperature and radiation can clearly be seen on both cavity lengths. However, the random variation in the processed data is significant. This variation has not been observed in previous results with this sensor under furnace testing. The magnitude of this variation is on the order of the parameters that are attempting to be measured, which prevents any strong conclusions about the index of refraction and/or compaction of the optical fibers.

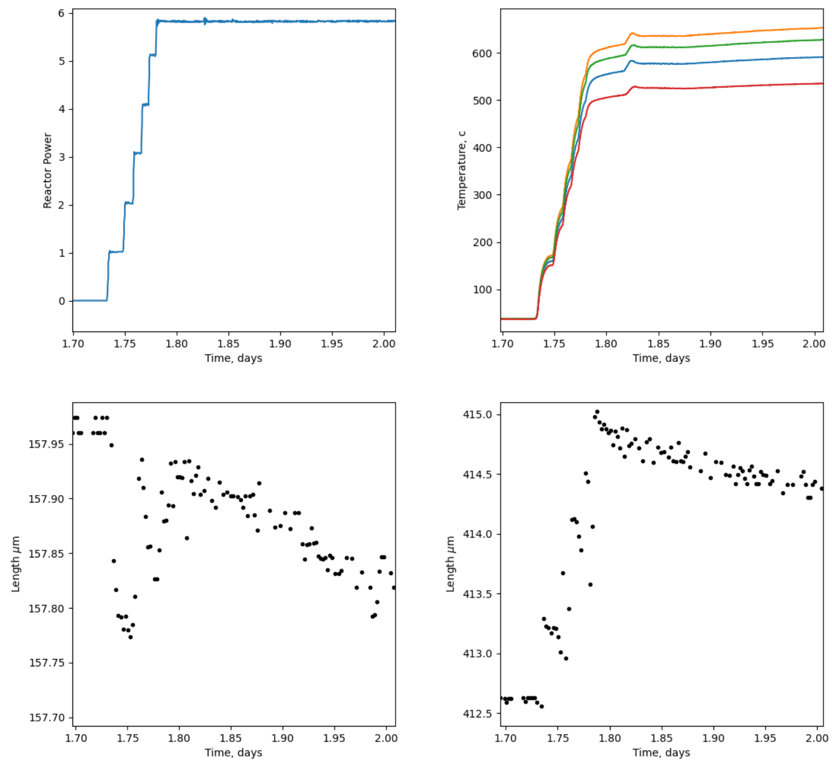

Figure 6 Snapshot of the reactor power (top left), temperature (top right), and the cavity lengths determined from the spectra (bottom left & right).

Currently, it is not clear if the sensor noise is related to the radiation environment, data reduction process, physical behavior of the sensor, or due to the fiber interrogation equipment. The analysis of this irradiation data is ongoing with a specific attempt to understand this variation and minimize it to draw useful conclusions about the glass behavior. Additionally, changes to the data reduction process are underway to improve the precision of the length measurement from the raw spectrum.

Previous furnace-based testing of the sensor utilized a Micron Optics Si155 fiber optic interrogator to collect the reflected spectrum from the cascaded Fabry Perot cavities. This irradiation utilized a Luna Innovations Optical Backscatter Reflectometer (OBR) to interrogate this sensor, in addition to other fiber optic sensors. Similarly, this device collects optical backscatter spectrum, but could be a potential source for variation compared to previous data.

Summary & Discussion

A significant amount of data has been collected from the active compensation sensor during irradiation in the Massachusetts Institute of Technology nuclear reactor. The processing of this data has been initiated and has provided intriguing results. Specifically, the random fluctuation in the determined cavity lengths is more predominate than previous results. The precision obtained with the current analysis procedures explained in this document are insufficient to provide useful information about index of refraction or compaction. This is predominately due to the random variation being on the same order of magnitude as the mechanism to be measured. This has not been the case previously and is unclear what the cause is for this behavior. This is the first in-pile test of this sensor, and therefore could have some impact on this random behavior. Additionally, this is a different fiber optic interrogation device than what was previously used. While it should be equivalent to the previous technique, it has not been ruled out as a potential source of this variation. Finally, there could be some unforeseen damage to the sensor causing some excessive variation in the readings. Data from the active compensation sensor in an upcoming irradiation in the BR2 reactor will provide a good comparison to the data presented here. The Micron Optics Si155 will be used for that data collection, which will provide a nice juxtaposition with this data. The data analysis from these irradiations will be completed as part of fiscal year 2024 activities.

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