

Corrosion Monitoring in Aging Aircraft Using Optical Fiber-Based Chemical Sensors

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ABSTRACT

A novel system using optical fiber long-period grating (LPG)-based chemical sensors for nondestructive corrosion detection is presented. Experience has shown that corrosion may be managed but not eliminated, hence reliable corrosion detection and quantification systems are required even in light of on-going corrosion prevention programs. In general, by the time corrosion is detected by manual surface inspection methods the damage is so extensive that expensive repairs are required. The development of distributed, embeddable, real-time optical fiber sensors capable of detecting corrosion by-products in otherwise inaccessible regions of an aircraft would eliminate a significant portion of the maintenance costs related to corrosion. The presented LPG-based corrosion sensors can be rendered insensitive to temperature effects and multiplexed in large numbers along a single optical fiber. This corrosion system has already been demonstrated for the detection of moisture, pH, and metal-ions and offers enhanced capabilities in the detection of numerous chemical and biological targets. The methodology behind sensor operation and applications of embeddable LPG-based corrosion sensors within simulated lapjoints is described.

INTRODUCTION

Corrosion related degradation of the aging aircraft fleet has proven to be costly to repair, causes reduced availability and service lifetime, and results in potentially unsafe operating conditions. Although there are several preventative techniques being developed to address this problem, the need for cost-effective and reliable methods for monitoring corrosion continue to exist. It is preferable to detect corrosion in the earlier stages because repairs are generally less expensive and corrosion tends to synergistically work together with other degradation mechanisms at an accelerated rate once it has begun. To protect aircraft structures from the initial onset of corrosion, organic coatings are applied to aircraft alloy parts. These coatings can successfully

delay the onset of corrosion but if the coating is compromised by cracking or UV degradation, leading to water leaking into the aircraft joint, the initiated corrosion can then spread extensively before being detected [1]. Some of these aircraft areas are often inaccessible and require costly disassembly for inspection placing emphasis on the prevention, detection, and understanding of the corrosion process.

Optical fiber sensors have been well demonstrated for determining chemical and physical parameters in a variety of harsh environments because they are resistant to attack by most chemicals and can withstand a wide range of temperatures. Optical fiber is also immune to electromagnetic interference, light weight, inherently small and has a flexible geometry. Performance characteristics such as these make optical fiber sensors ideal for the detection of corrosion in hidden and inaccessible regions of aircraft structures. By developing sensors that can detect precursors to corrosion such as moisture, pH, and metal-ion corrosion by-products, the severity of the corrosive environment can be determined and the predictive health of infrastructure can be evaluated. LPGs are designed to act as spectral loss elements that couple a discrete wavelength of light out of the optical fiber as a function of the surrounding refractive index. By applying special coatings that change refractive index with absorption of target molecules to the LPG surface, the optical fiber sensor becomes a transducer for chemical measurement. This paper presents accomplishments to date on moisture detection within simulated lapjoints using LPGs coated with a polyethylene oxide (PEO) polymer blend that swells and changes refractive index in the presence of moisture.

SENSING METHODOLOGY

First demonstrated by Vensarakar, et al. in 1995 for use in the telecommunication industry as a spectrally selective bandpass filter, the long period grating (LPG) has also been designed for strain, temperature, and refractive index sensing [2]. As a refractive index sensor, the LPG operates by scattering light out of the core at a particular wavelength based on the grating period, the optical fiber index profile, and the surrounding refractive index [3]. By applying a coating that changes index of refraction based upon the absorption of the environment targets, determination of the environmental corrosivity can be accomplished.

For the detection of moisture, long period gratings were coated with a PEO-based hydrogel that swells in the presence of moisture. The optical spectrum of a PEO coated LPG sensor was monitored by injecting a broadband light source into the sensor and monitoring the change in the spectral output using an optical spectrum analyzer. The transmission spectrum obtained from the sensor in a dry coating state, as shown in Figure 1, has no spectral loss dip. The spectral loss dip is not visible in the transmission spectrum, because the index of refraction of the coating exceeds that of the fiber cladding. A higher coating index prevents coupling from the core mode into the higher-order cladding modes. However, once the sensor is submerged in water, the effective index is decreased and the familiar LPG loss dip returns to the spectrum. These sensors can be operated at various wavelengths to allow for multiplexing capability. Once the sensor is removed from the water bath, the original flat transmission spectrum is observed. Hence, the PEO coated LPG sensor displays rapid response time, as well as good reversibility and repeatability.

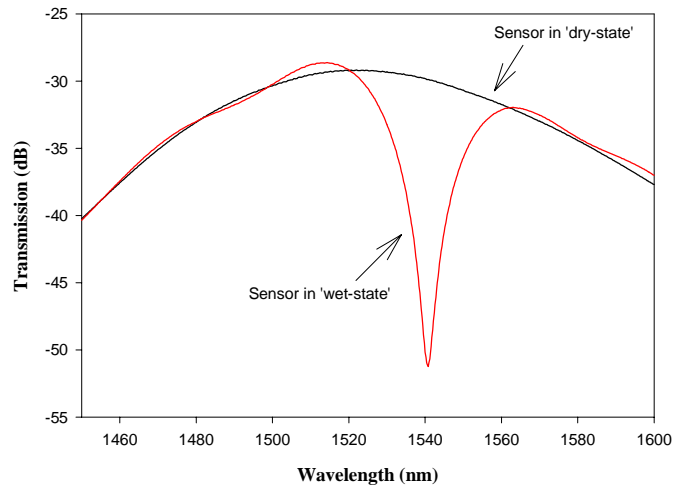


Figure 1. Optical spectrum of LPG-based moisture sensor submerged in air and water.

For interrogation of the presented LPG-based moisture sensors, the demodulation system, shown in Figure 2, was assembled. The system includes a signal-conditioning unit consisting of support optics, a laptop computer with application specific software, and an optical switch for interrogating an array of sensors. With this system, up to eight simulated lapjoint specimen can be monitored simultaneously.

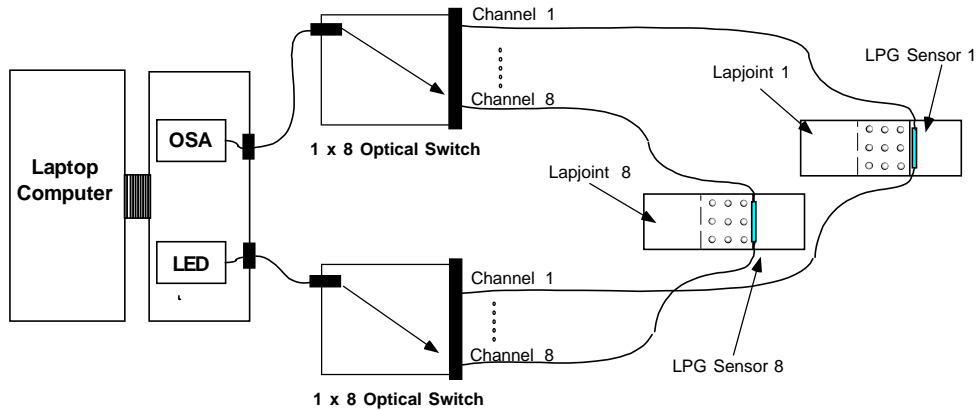


Figure 2. Schematic of LPG interrogation system using dual 1x8 optical switches and a computer interface.

The software GUI interface developed to support the LPG-based moisture sensors is shown in Figure 3. This software has a special algorithm that tracks the spectral loss dip of the LPG versus time after it appears and water is detected. This data provides information as to the time of wetness within the measured environment. Currently the system displays a low wavelength when there is no spectral loss dip, as illustrated by Channels 3, 4, 5, and 8. As shown, sensors on Channel 6 and Channel 7 have been exposed to water and have responded with an increase in wavelength. This software gives the user the capability of displaying all the channels at once or

selecting individual channels to display. All data can also be saved to a text file for post processing.

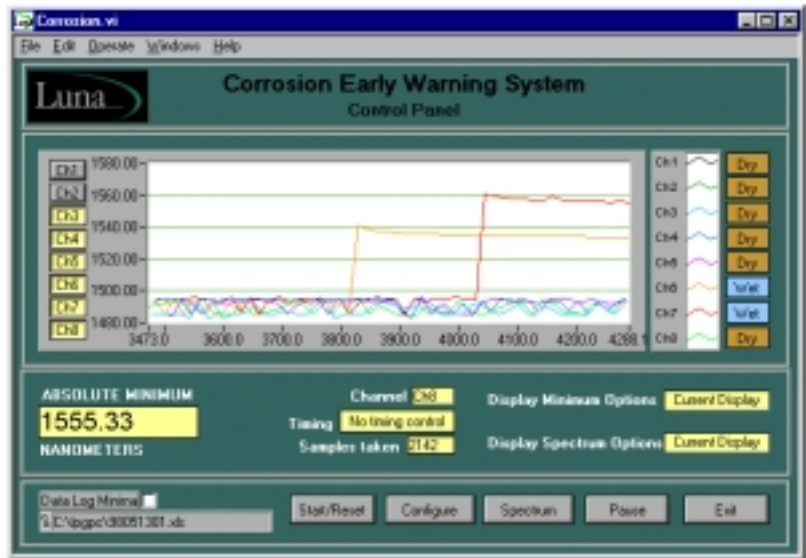


Figure 3. GUI Interface showing time vs. LPG wavelength and status (wet/dry) for each activated channel.

The software also allows the user to display the raw optical spectrum for each channel. Figure 4a shows the optical spectrum of an LPG-based moisture sensor in the dry-state. There is no visible spectral loss dip for this sensor when it is dry. In this state, the Lunascan software tracks the lower end of the spectrum. When the sensor is exposed to water the spectral loss dip appears at a predetermined wavelength, as shown in Figure 4b. The wavelength of this spectral loss dip can be tracked by the Lunascan software, as illustrated previously in Figure 3.

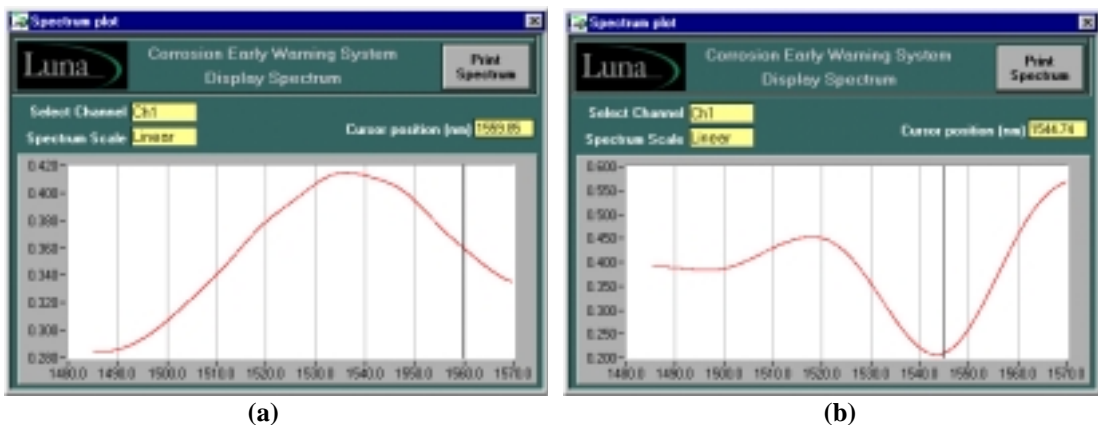
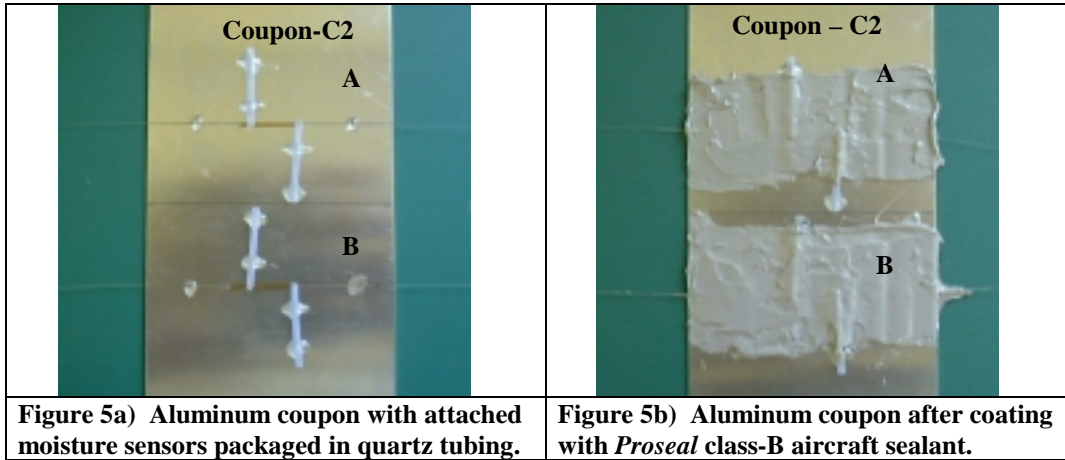


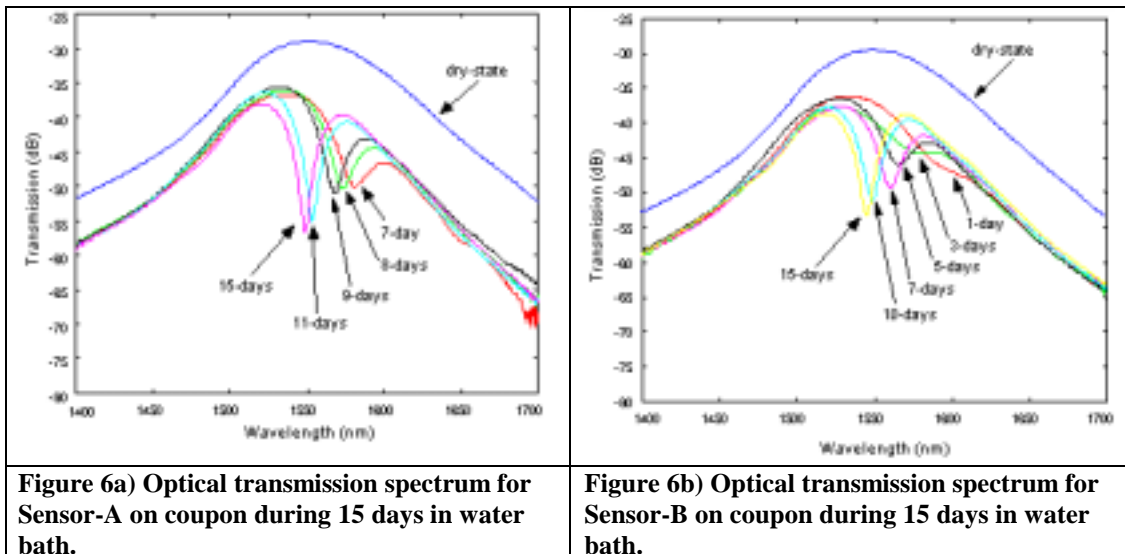
Figure 4. GUI Interface showing optical spectrum output for moisture sensor in dry-state and in wet-state, a) typical optical spectrum for LPG-based moisture sensor in a dry-state, and b) typical optical spectrum for LPG in a wet-state.

RESULTS

To demonstrate the sensing capability of the LPG-based moisture sensors in embedded applications, several sensors were attached to aluminum coupons under lapjoint sealant and monitored daily for a response to water penetration. The photograph in Figure 5a shows the aluminum coupon before *Proseal* class-B lapjoint sealant is applied over the sensors. These moisture sensors were packaged in a quartz tubing and then attached to the aluminum coupon. In this demonstration small access tubes were used to allow water to flow to the sensor for accelerated sensor evaluation. Once the lapjoint sealant was applied to the aluminum coupon it was allowed to cure for 19 days and then the entire specimen was submerged in water for 15 days.



The plot shown in Figure 6 is the history of spectrum plots for Sensors A and B, attached to the aluminum coupon, shown in Figure 5. These plots show no spectral loss dip when the sensor is in a dry-state, and as the coupon is exposed to water the spectral loss dip appears and continues to develop until it reaches the saturation point. The difference in sensor response time is due to a difference in water penetration from location to location. The placement of the access tubes or quality of the sealant around the sensor effect the rate at which water enters the sensing region.



Water Detection Within Simulated Lapjoints

To evaluate sensor performance under simulated flight conditions, lapjoints with embedded sensors were fatigued and exposed to a corrosive environment in a salt spray chamber. The specimens were prepared by attaching LPG-based moisture sensors at the crevice of non-cladding coated simulated lapjoints assembled from Al-2024. Aircraft sealant was applied over the sensors and allowed to dry. Figure 7 shows a photograph of a typical simulated lapjoint assembly with LPG-based moisture sensors embedded within the crevice under lapjoint sealant. After allowing the lapjoint sealant to completely dry, the simulated lapjoints were fatigue cycled with 2500 lbs tension for 30k cycles at 10 Hz. The lapjoints were then submerged in a salt spray chamber for 13 days. Figure 7b shows a photograph of the lapjoint after the fatigue/corrosion process.



Figure 7a. Photograph of simulated lapjoint with embedded long period grating-based moisture sensors in lapjoint crevice under aircraft sealant.

Figure 7b. Photograph of simulated lapjoint after fatigue cycling and exposure to salt spray chamber for 13 days.

The sensor response from the LPG-based moisture sensors was acquired by injecting a broad band light source into the optical sensor and interrogating with an optical spectrum analyzer. Figure 8 shows a typical unprocessed optical response from the LPG-based moisture sensors embedded within the lapjoint sealant. The sensor detected water penetration into the lapjoint after approximately 23 hours of exposure in the salt spray chamber, which resulted in the appearance of the spectral loss dip at 1555 nm.

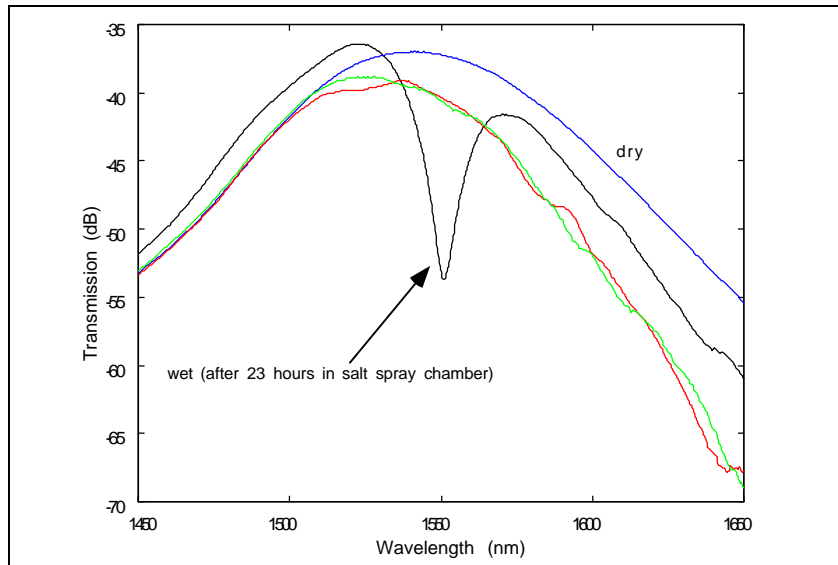


Figure 8. Optical spectrum captured from moisture sensor embedded in simulated lapjoint that was fatigue cycled and exposed to salt spray.

Simultaneously the LPG sensor response was interrogated using the prototype signal-conditioning system and software to monitor time-based data. Figure 9 shows the data acquired from the same sensor that generated the spectrum shown in Figure 8. After 23.06 hours (83,000 seconds) the spectral loss dip appears at 1563 nm and slowly saturates to the left until it reaches 1555 nm. Future testing is slated for embedding LPG-based pH, metal-ion sensors in addition to the moisture sensors within simulated lapjoints and conducting similar fatigue cycling and environmental exposure. Results from these tests will be compared with other current non-destructive inspection tools.

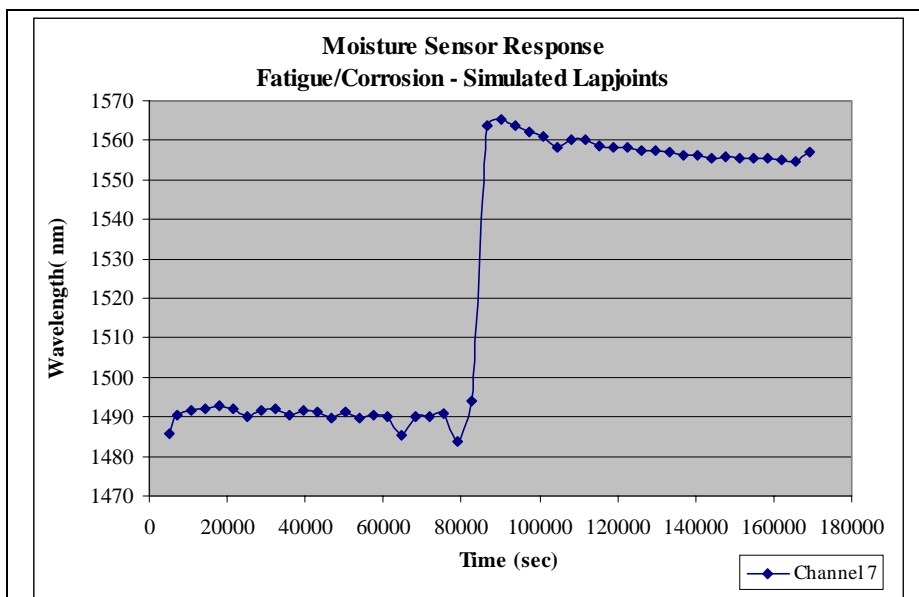


Figure 9. Sensor response to moisture acquired using prototype long period grating signal-conditioning system.

CONCLUSIONS

The presented long period grating-based sensors demonstrates the capability for continuous monitoring of corrosive activity to reduce maintenance costs as well as offer an overall health monitoring approach for future aircraft that require extended operation lifetimes. This sensing platform not only shows promise as a next generation NDE tool for aging aircraft, but also shows promise as a laboratory tool for acquiring a better understanding of corrosion within lapjoints and as an evaluation tool for corrosion preventative compounds and other corrosion preventative techniques. A sensing platform incorporating LPG-based chemical sensors is also capable of validating other NDE techniques, as well as facilitating atmospheric corrosion studies and environmental exposure correlations. Future research will continue to develop the LPG-based sensing platform for corrosion monitoring with focus on an overall understanding of early stage development. Other applications that benefit from the unique sensing advantages the LPG offers include: biological sensing for detection of food and airborne pathogens, and chemical sensing for environmental and industrial process monitoring.

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