Final Report:
Revolutionary Aeropropulsion Concepts
Miniature Autonomous Sensors and Actuators for Smart Propulsion Systems:
Integrated Photonics

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Introduction:

The Glenn Research Center (GRC) main role inside the National Aeronautics and Space Administration rests in the research for the optimization of today’s aerospace propulsion and power technology, as well as the development of new devices, ideas and techniques. Thanks to our daily effort, we have achieved improvements in many technology areas, specially for aerospace and aeropropulsion applications.

One of our challenges in GRC's Instrumentation & Controls Division has been the optimization of aircraft performance, such as noise reduction, instrumentation development for engine diagnosis and repair, smart materials and components, wireless communication systems, improved performance at high temperatures, technology miniaturization and many others.

The Revolutionary Aeropropulsion Concepts (RAC) project plays an important role in these efforts. It is divided in several tasks and sub-tasks, in order to organize and fulfill the goals of such an extensive and multifaceted project. During my Co-op experience, I became part of a team of professionals and highly qualified engineers working for RAC, specifically in the Integrated Photonics area.

Since this is a research project, the following report will include a brief description of the project tasks and technical challenges, optical technology and material concepts, and my collaboration to such a great effort, which will eventually result in a great benefit for NASA and the entire aircraft industry.
REVOLUTIONARY AEROPROPULSION CONCEPTS PROJECT

Task: Miniature Autonomous Sensors and Actuators for Smart Propulsion Systems

Sub- Tasks:
- Integrated Photonics
- Stable Electronics Device Demo
- High Temperature, High Frequency Actuators
- Mobile Maintenance Devices

Objective:
The development of an intelligent system using integrated miniature sensors, electronics and actuators for engine self-diagnosis, self-reconfiguration and self-repair.

Approach:
- Develop miniaturized (micro- or nano), durable components compatible with engine operating temperatures.
- Develop embedded microsystems to integrate sensing, signal process, actuation, and communications into structural components.
- Develop micro- roving systems to move autonomously through an engine.
- Develop algorithms for controls and demonstrate on integrated sensor/actuator.

Technologies Involved:
- Integrated photonics for sensing, communication and actuation
- Reliable electronics for data processing and wireless communication
- Actuators with large force and high frequency capability
- Mobile maintenance devices for autonomous inspection

Technical Challenges:
- Sensor integration in structures and operation in engine environments
- Stable high temperature electronics and sensors
- Actuators for self configuration in high temperature environments
- Systems to perform engine diagnosis and repair
- Control systems to interpret signals and determine appropriate action in a smart vehicle
Sub-Task: Integrated Photonics

Objective:
Instrumentation of component parts e.g. blades and/or disks with an array of embedded sensors to detect damage.

Description:
This task will use a range of photonic-based technology to detect damage in engine parts and components. Such photonics systems includes light sources, sensors, interconnects, and multiplexing systems. The activities planned for the fiscal year 2001 are:

- In order to demonstrate integrated photonic sensing to determine damage to a part, a coupon will be instrumented with an array of Fiber Bragg Grating (FBG) sensors. This coupon will be vibrated externally, and measurements will be taken of the spectral signature from the gratings. The coupon will then be damaged and the spectral signature will be re-measured. In addition, it will be subjected to the curing process and their performance will be evaluated at those temperatures. The signal will be analyzed for each experiment, to determine the extent that damage to a part can be measured by this technique. The monitoring of the curing process of polymer matrix composite materials (PMC) is an essential part of this effort.

- Determine feasibility seal leakage using Bragg temperature sensors. Concept requires heat addition into the measurement volume. Determine whether or not sufficient IR radiation can be delivered via optical fibers.

- Purchase equipment to enable in-house fabrication of a micro-optical white light source. This source can be used to power optical devices such as the Fabry-Perot exhaust gas temperature sensor.

Technologies Involved:
- Optical Fiber Bragg Sensors
- Microfabrication Technology
- Optical Instrumentation

Technical Challenges:
- Integration of sensors into structures and to have those sensors still be operational in engine environments.
- Multiplexing large numbers of spectral signals.
- Microfabrication of a micro-light source, which can operate at temperatures high enough to generate light with an adequate lifetime.
Optical Fiber Bragg Grating Sensors

How does a Fiber Bragg Grating Sensor works?

Optical Fiber Structure:

An optical fiber is a dielectric waveguide that operates at optical frequencies \((10^{14} - 10^{15}\text{ Hz approximately})\). This fiber waveguide is normally cylindrical in form. It confines electromagnetic energy in the form of light to within its surfaces and guides the light in a direction parallel to its axis. Basically, it has three main parts: the core, with an index of refraction \(n_1\) and through which the signal travels, the cladding, with an index of refraction \(n_2\) that is less than \(n_1\) and the buffer coating or jacket. This jacket protects and gives flexibility to the fiber, while the cladding-core interface, where \(n_1 > n_2\), keeps the signal traveling inside the core.

![Fig.1 Schematic of a single-fiber structure](image)

This signal travels through the optical fiber in many ways. Its propagation through the core is described in terms of a set of electromagnetic waves called modes. A fiber that sustains only one mode of propagation is called a single mode fiber, whereas a multimode fiber contains many hundreds or even thousands of modes. The fibers that I used for my experiments were all single mode fibers.

![Fig.2 Comparison of single mode and multimode optical fibers](image)
**Fiber Bragg Gratings:**

Fiber Bragg gratings (FBG) are formed by periodic variations in the refractive index of the fiber core that act as semitransparent-semireflective interfaces or surfaces. When light propagates through the FBG, some of it is reflected by these interfaces, in which case the FBG works as a filter, allowing only light of a certain wavelength to be reflected back. This particular wavelength is called the Bragg wavelength. The principle of a FBG operation and relationship between the parameters of the FBG and the Bragg wavelength are shown in Fig. 3.

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**Fig. 3**  *Graphical representation of FBG and formation of resultant signal.*

- $\lambda_B =$ wavelength of the reflected signal or “Bragg wavelength”
- $\bar{E} =$ period of the FBG
- $n =$ effective index of refraction (an average of the slightly higher index of the grating and the lower index of the regular fiber core)

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**Fig. 4**  *Spectra of light propagating through an FBG*

A) Shape of initial signal spectrum.
B) Resulting shape for transmitted signal. The “missing” part reflected from the initial spectrum can be observed.
C) Reflected signal spectrum.
Why Optical?

Fiber optic technologies have several advantages over other kinds of communication devices. They offer low attenuation, wider bandwidths, small physical size and weight, reduced number of required wires and repeaters, large information-carrying capacity, immunity to lightning and electromagnetic interference (EMI), high degree of data security, freedom from cross talk between fibers, and a virtual independence from signal frequency, which eliminates the need for equalization circuitry.

Why use Fiber Bragg Grating Sensors?

In addition to the fact that they share most of the advantages described before, FBG sensor systems have the potential to offer many other advantages over conventional sensors, such as increased safety, reduction in cost and complexity of the hardware, resistance to corrosion, multiplexing capability, etc.

One of the major problems with conventional sensor systems is the cabling. For the long distance monitoring, these cables will suffer from the EMI, which deteriorates the signal-to-noise ratio of the output. This cabling problem can be reduced significantly with the use of optical fiber sensors, which can carry input and output light over the same strand of optical fiber without suffering from electromagnetic interference. An FBG sensor is also wavelength-encoded, and gives an absolute measurement. This method avoids the problems with scale resetting and signal intensity variation. In addition, we can multiplex several sensors onto the same optical fiber, which is particularly useful in applications like ours, where multiple sensing points distributed over an area may be required.

In particular, the multiplexing ability coupled with a high spatial resolution of this kind of sensor makes it the best candidate for monitoring civil infrastructures, such as bridges, highways, buildings and dams. Due to its multiplexing capability, FBG sensors also show a great potential for applications in the field of distributed sensing in “smart structures”, into which FBG sensor arrays can be embedded to measure parameters such as strain, stress, temperature, cracks, acceleration and vibration of the structures. A network of fiber optic sensors can allow the structure to monitor its integrity or health during manufacturing and service. Moreover, these sensors could replace many of the functions traditionally performed by human visual inspection and could provide a real-time feedback in the event of structure failure.

Polymer Matrix Composite Materials

What is a Polymer?

The term “polymer” is derived from the Greek “poly”, meaning “many” and “mer”, meaning “parts”, so polymers are substances made of “many parts”. In most cases the parts are small molecules, which react together hundreds, thousands, or millions of times. The resulting molecules may be long, straight chains, or they may be branched, with small chains extending out from the molecular “backbone”. The branches also may grow until they join with other branches to form a huge, three-dimensional matrix or PMC.
Chemistry of PMC Materials

Basically, the Polymer Matrix Composites (PMC's) developed at NASA, Glenn Research Center are all of the same type. They are formed by the reaction of an anhydride with an amine. This reaction occurs rapidly, even at room temperature, which limits the shelf life of the unprocessed material. In order to slow down this process, the anhydrides are converted to ester-acids, which won't react with the amine but will convert back to anhydride at processing temperatures above about 100 °C.

However, the polymer gets so thick that the water and methanol generated by the reaction can't escape easily from it, resulting in a composite with trapped volatiles, which tend to have voids (interior holes). To solve this problem, a monofunctional ester-acid is added to the mixture. Whenever one of these monomers react, it stops the growth of one end of the chain, resulting in relatively short chains. However, by adjusting the properties of the three monomers, the average chain length can be controlled. The endcap used to solve this last problem was the ester-acid of Nadic anhydride. This endcap is made to react with other endcap molecules at higher temperatures, forming a relatively low molecular weight chain that can still melt, allow volatiles to escape and provides a way to connect these short chains together to get the benefit of having a 3-dimensional polymer.

Why use Polymer Matrix Composite Materials?

The advantages of replacing metals in aircraft turbine engines with high-temperature polymer matrix composites include weight savings accompanied by strength improvements, reduced part count, and lower manufacturing costs. These materials are exhibiting such high strength-to-weight ratios that they are finding increasing applications not only in the aerospace industry, but in the automotive industry as well. In addition, these composites are occasionally used in high performance materials where the complex structures impart exceptional strength, thermal stability, electrical conductivity, and other desirable properties.
My Tasks

I. Evaluation of the FBG Sensor Response during PMC’s Curing Process

A. Preliminary evaluation of data recorded during PMC’s curing process

Description:

My first task as part of the Integrated Photonics team was the evaluation of data recorded during the curing process of 4 identical panels made of polymer matrix composite (PMC) materials. Fiber Bragg Grating (FBG) sensors were embedded in the panels, to monitor the changes occurring during this process and evaluate their response (See Fig.6).

![Polymer composite plate with an embedded fiber optic Bragg grating.](image)

Fiber optic pigtails that are coming out of the two opposite sides of the plate belong to the embedded fiber optic grating, which is therefore not visible.

A super luminescent light emitting diode (SLED) was used to transmit a signal through each single-mode fiber, to measure parameters such as temperature, pressure, stress, strain, etc. The raw data (wavelength, intensity, temperature and time) was collected before my arrival and I was given the job to process and analyze it. (see Fig.7). To compare the temperature-time data with the Bragg wavelength and power intensity of the signal received, I used Axum 6.0, a graphing and data analysis program, coupled with Axum S-Plus programming language. (see Fig.8) (Because the curing process of the first panel was different than the others, I mostly worked with the last three. Repeatability in the behavior of these parameters is essential in order to understand and calibrate the signal.)
Fig. 7 Data recorded during panels’ initial curing process
(A) Temperature-Time data
(B) Intensity-Wavelength data as recorded by FBG

Results:

As we can see in figure 8, the Bragg wavelength value increased and decreased almost at the same time as temperature. All three panels followed this same pattern.

Fig. 8 Relationship between wavelength and temperature.
(A) Temperature history of the three panels
(B) Wavelength of the light reflected from the FBG during curing process.
However, this was not the case for the power intensity, where the signal recorded for the three panels behaved differently for each one of them.

Fig. 9  Relationship between intensity and time during the curing process, as sensed by the FBG.

Explanation of Results:

As it was established in figure 3, the Bragg wavelength value is defined by the equation $\lambda_B = 2 n \Lambda$, which indicates that it is directly proportional to the period of the FBG. As the panel temperature increases, thermal expansion will occur, resulting in an increase of the period of the grating and therefore the Bragg wavelength. The opposite thing may happen as the material cools down and shrinks the FBG back to its original position. Till this point, the changes in power intensity as a function of temperature were not understood. A possible change in the PMC-cladding interface was considered, but this was not yet confirmed.

B. Conduction of Thermal Tests

Description:

After evaluating the data recorded during the initial curing process of the panels and because of the inconclusive results I had, we decided to perform some thermal tests on them, to evaluate the FBG response again.

Each panel was placed inside a box furnace, while a 150 mA SLED signal was sent through the FBG. The furnace was programmed to heat up at a rate of 2°C per minute from room temperature (~26°C) to 300°C and to hold that last temperature for 2.5 hours. A thermocouple was placed inside the oven to keep track of the “real” panel temperature. After that, the panels cooled down naturally for 1 hour, 40 minutes. Then, the furnace door was opened to accelerate their cooling process. An optical spectrum analyzer was programmed to record the signal wavelength and power intensity data every five minutes from the beginning to the end of the tests.
In order to have more accurate results, the tests were performed three times for each panel, and the data process and analysis of results.

Setting:

As we can see in figure 11, a SLED signal (green arrow) comes out of the power supply, and finally reaches the FBG. Then a part of that spectrum is reflected from the gratings (blue arrow) back through the coupler and the orange cable, which connects to the optical. The glycerin at enabling a more accurate reading and a clearer image in the analyzer.
The optical spectrum analyzer was programmed as follows:

```
01  RESOLN MAXIMUM
02  SPAN 10.0 nm
03  WRITE A
04  DISPLAY A
05  ACTIVE TRACE A
06  FIX B
07  BLANK B
08  FIX C
09  BLANK C
10  N= 10
11  REPEAT
12  SAVE TRACE A
13  SAVE EXECUTE
14  WAIT 300 s
15  N= N-1; IF N<>0 GOTO 4
```

- Writes the signal trace A and ignores traces B & C
- Records data in floppy disk every 5 minutes
- Sets an infinite loop on purpose. The analyzer will keep recording data until the floppy disk is full.

The technology that I used was:

- Box Furnace- model 6-525, Ney Co.
- Optical spectrum Analyzer - model AQ6330, Ando Co.
- Power Supply - SOA Controller V4.0; SLED 1300S5A / D127, OPTO SPEED SA
- Thermocouple- DORIC Trendicator, 400A
- Fiber Bragg Grating: 1300-85-0.3P

**Results and Discussion:**

The following figure describes the furnace temperature behavior during the test before its door was opened. Both the wavelength and power intensity of the signal were expected to change accordingly.

![Furnace Temperature Behavior](image)

**Fig. 12 Furnace Temperature Behavior**
Although the signal wavelength still follows the panel temperature, the results obtained from these tests were clearer and a lot more predictable than the first ones (see Fig. 13). Each panel held its highest Bragg wavelength for approximately 2.5 hours, which was exactly the time that the furnace held 300 °C. They also show an abrupt change during the cooling process, which occurred exactly when the furnace door was opened.

![Wavelength vs Time](image1)

**Fig. 13** Relationship between wavelength and time, as sensed by the FBG for the following:
(A) Panel 2  
(B) Panel 3- In test 2 the door was opened 15 minutes later  
(C) Panel 4- In test 3 the door was opened 25 minutes later

The following figure is an example of how accurately the Bragg wavelength value was following the temperature changes inside the furnace. Similar comparisons can be made with the rest of the panels.

![Wavelength / Temperature vs Time](image2)

**Fig. 14** Relationship between wavelength, temperature and time as sensed by FBG in Panel 2. The black plot stands for the furnace temperature change in time.

Although the power intensity change wasn’t as predictable as the wavelength change in time, the results for this test were still better than the first one because of the similarities in some characteristics of the graphs (see Fig.15). All of them increased as temperature was increasing and
reached their maximum when the temperature reached 300°C as well. In addition, the power intensity value decreased approximately when the cooling process of the panel started and changed abruptly when the furnace door was opened. Again we can see how the signal was affected in Panel3, test 2 and Panel4, test 3, where the door was opened at a different time. However, these readings experienced significant changes as more tests were performed, specially on Panel 3 (the last panel I worked with), were I found a difference of almost 20% between the f. In this particular case, the power intensity data was plotted relative to its initial value (see Fig.15B).

Fig. 15  *Relationship between power intensity and time, as sensed by FBG.* The red, blue, green and black colors define the power intensity path in tests 1, 2, 3 and 4 respectively for the following:
(A) Panel 2  
(B) Panel 3  
(C) Panel 4

The following figure compares Panel 2 power intensity data with the temperature changes occurring inside the furnace. A similar behavior was found for each one of the panels.

Fig. 16 *Relationship between intensity, temperature and time as sensed by FBG in Panel 2.* The blue graph stands for the temperature behavior inside the furnace, and the red graph for the power intensity of the signal in:
(A) Test 1  
(B) Test 2  
(C) Test 3

Even though the shape of the graphs was different for each test, this figure clearly showed the similarities in the characteristics discussed before. In each case, the power intensity increased almost linearly with temperature, reached its maximum at 300°C and decreased as the panel cooled down.
Hypothesis:

After performing these temperature tests, it became more evident that the Bragg wavelength shift is quite linear to the temperature profile, even when changes such as opening the door at different times occurred. Therefore, the hypothesis established before was once again proved. As for the power intensity profiles, more accurate conclusions can be made. The power intensity increased and decreased almost linearly with temperature, which may be due to several reasons.

If we look at the structure of an optical fiber and how a signal travels inside of it, we will see that although most of the light propagates inside the core, some of it will still escape through the cladding (see Fig.17A). But if the area of the fiber expands as temperature increases, a larger amount of that light will be able to travel inside the core, allowing the optical spectrum analyzer to record an increased amount of power (see Fig.17B). The opposite thing may occur when the panel starts to cool down and shrinks the fiber back to its original size.

Fig. 17  Optical fiber expansion with increasing temperature

If we look at the temperature profile of the panels, 300°C were kept for approximately 2 hours and 30 minutes. During this period of time, the power intensity value fell and started to fluctuate until the cooling process started, when in most of the cases, it increased for a little while and then decreased gradually in a very similar way for each panel. Keeping 300°C for so long might be the principal cause for this abrupt decrease and the fluctuations in the optical power.

If we look at the initial curing process profile (Fig.8A), the highest temperature wasn't held for as much time as we did in these tests and the panels ended up in perfect conditions. However, after the thermal tests were performed, we notice a considerable damage in the shape of the panels, which may be caused by thermal stresses or internal differential thermal expansion during the process. If this is true, the stresses may alter the shape of the fiber and therefore the signal that passes through it. In addition, the close proximity of the polymer and the fiber core may change its index of refraction with temperature, affecting the amount of light coupled out of the fiber core and dissipated in the cladding. Therefore, the amount of power that the analyzer is able to read will change. Because of the differences in the signal behavior from one panel to the other, a possible problem or variation in the light source was also considered.
II. Preliminary Evaluation of Mechanical Properties of the FBG Sensor

Setting Description:

In addition to the FBG evaluation during the PMC’s curing process, I performed some other tests on the fibers alone. An optical FBG sensor similar to the ones that were embedded in the panels was used to measure its overall performance under strain conditions.

As we can see in figure 18, the Bragg grating area of the fiber was placed between a metal holder and a micrometer at a certain distance L. The ends of this area were previously glued to two pieces of metal with a 608 clear epoxy resin and hardener to keep the fiber in place at all times. The rest of the fiber was connected to the power supply and the optical spectrum analyzer as it was done for the temperature tests.

![Fig. 18 Setting Schematic for Strain Analysis](image)

Using the micrometer, an increasing amount of tension (distance change ÄL= 0.01 mm at a time) was being applied, and the corresponding wavelength shift seen in the analyzer was recorded manually. Since strain and ÄL can be related by the equation: \( \text{Strain} = \frac{\Delta L}{L} \), I used Axum S-Plus to convert the ÄL data into strain data and compared it with the wavelength changes of the signal. This test was performed five times for the same FBG sensor.

The specifications of the FBG used were:

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Product Number:</td>
<td>1300-0.3 A-P-O</td>
</tr>
<tr>
<td>Serial Number:</td>
<td>G318</td>
</tr>
<tr>
<td>Center Wavelength:</td>
<td>1300.00 nm</td>
</tr>
<tr>
<td>Bandwidth:</td>
<td>0.3 nm</td>
</tr>
<tr>
<td>Reflectivity:</td>
<td>&gt; 91%</td>
</tr>
<tr>
<td>Pull Test:</td>
<td>&gt;100 kpsi</td>
</tr>
<tr>
<td>Annealing at:</td>
<td>300°C</td>
</tr>
<tr>
<td>Fiber Pigtails:</td>
<td>≥ 1.0 m</td>
</tr>
<tr>
<td>Fiber Type:</td>
<td>Polyamide</td>
</tr>
<tr>
<td>Packaging:</td>
<td>Polyamide recoated</td>
</tr>
</tbody>
</table>
Results:

The following figure is a summary of my results for this test:

![Graphs showing Wavelength vs. ΔL and Wavelength vs. Strain](image)

Fig. 19  Relationship between: (A) Wavelength and ΔL  
(B) Wavelength and Strain

For the first 0.44 mm (200 micro strains) applied in each test, the Bragg wavelength increased almost linearly at a rate of 1.21 nm per m strain. But as I kept stretching the fiber, it became more and more sensitive to this changes and the wavelength value followed a different path for each test. However, we can still see some similarities between tests 2 & 3 and tests 4 & 5.

Explanation of Results:

Once again, the wavelength changes are directly associated with the period of the fiber gratings. As the fiber stretched more and more, both the period of the grating and the Bragg wavelength value increased (see Fig.20), resulting in the graphs presented before. Both of them are practically the same, because they are directly proportional to each other ($Strain = \frac{\Delta L}{L}$). However, the more the fiber stretched, the more it tried to go back to its original position and therefore became progressively sensitive to these changes.

![Diagram showing change in grating period as fiber stretches](image)

Fig. 20  Change in grating period as fiber stretches

Since this experiment was performed manually, the time elapsed between one reading and the other was difficult to control from test to test, which gave the fiber more or less time to move back, causing the wavelength value to remain the same in some cases. Not knowing this before hand, I waited more time between readings in tests 2 & 3 than in tests 4 & 5. This explains the similarities between these pairs of tests.
Conclusion

When I first came to NASA, Glenn Research Center, I had many different goals in mind. Being in the middle of my studies, this experience represented an opportunity to explore different areas inside my majoring field and define my interests better. I wanted to improve my programming and computer skills, as well as to have more exposure to the applications of the theory learned in school.

Working in GRC Instrumentation & Controls Division, Optical Instrumentation Technology Branch, gave me the opportunity to participate in a variety of tasks, which helped me fulfill these goals. I learned many things, from leadership and report skills, to programming, signal processing and optical technology manipulation. Surpassing my programming phobia and optimizing my computer skills was one of my best accomplishments during this experience, as well as having the opportunity to run one of the tests by myself. Although some of the work I did wasn't directly related to my areas of interest, this gave me the opportunity to explore and expand my possibilities in the electrical engineering field as well as the technology exposure that I wanted, which I consider is one of the most important experiences that every engineer must have.

Taking care of such responsibilities, being able to share my work with other team members and becoming part of such a great project as RAC, was a very challenging and rewarding experience. For these and many other reasons, working at NASA, GRC has been one of the best educational experiences that I ever had, that helped me improve not only as a professional, but as a human being. Becoming part of the efforts and ambitious dreams of such a prestigious organization like NASA has been the best experience of my life, and a dream come true.
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