CONTINUOUSLY SWEPT LASER-BASED FIBER BRAGG GRATING DATA ACQUISITION SYSTEM CAPABLE OF OPERATING IN EXTREME ENVIRONMENTS

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ABSTRACT

Structural health monitoring (SHM) utilizing optical fiber sensing is attractive for various aerospace applications because of the lightweight nature of the fiber optics, the ability to cascade multiple sensors onto a single fiber, and its immunity to electromagnetic interference (EMI). Optical fiber sensing based on fiber Bragg gratings (FBGs) is an attractive candidate for strain and temperature sensing, especially in extreme environments such as a hypersonic flight. The National Aerospace and Space Administration (NASA) Armstrong Flight Research Center (AFRC) (Edwards, California) has more than two decades of experience integrating fiber-optic sensors into various flight aircraft as well as developing custom ruggedized interrogators to suit the requirements for each unique situation.

This paper presents, in detail, a custom-built data acquisition system (DAS) capable of detecting not only FBGs but also Extrinsic Fabry-Perot Interferometers (EFPIs). Presented as well, and again in detail, are the system design, environmental testing under vibration, and thermal cycling.

INTRODUCTION

For aerospace applications, nondestructive evaluation (NDE) of an aerospace structure is paramount for the health of the aircraft to consider its safety and reliability. Techniques such as in situ structural health monitoring (SHM) can assess the health of an aircraft for a potential failure, and by incorporating SHM as part of the NDE throughout the life cycle of the aircraft, downtime, which is associated with periodic inspection involving the disassembling of structural components, can be reduced.

Fiber-optic-based sensing is an attractive part of the NDE suite since the fiber sensors may be able to be integrated into the aircraft during its build-out process. Recently, NASA has been looking at the feasibility of utilizing fiber-optic sensors as part of the SHM suite [1,2]. The advantages of fiber-optic sensors, based on FBG, include the ability to multiplex multiple sensors into a single fiber cable, which reduces size, weight, and installation complexity. As fiber sensors use optical light reflection as the sensing element, problems such as electrical arcing or electromagnetic interference will not be an issue. This paper presents an interrogator suite that was developed by NASA AFRC. This fiber-optic sensor interrogator is based on a swept tunable laser with no moving parts and is designed to be ruggedized and capable of supporting extreme environments. The system is capable of monitoring up to eight 40-nanometer (nm) bandwidth channels simultaneously and can monitor both FBGs and EFPIs concurrently, on separate channels.

The following section presents a brief introduction of how FBGs and EFPIs work, followed by the concept of wavelength division multiplexing (WDM) as the operating principle of the interrogator. A design summary of the fiber-optics data acquisition system will be shown next with the novel technique of utilizing a continuously swept tunable laser with no moving parts. Then, data from operating in a subcomponent scale will be presented to verify performance as well as environmental testing such as vibration and thermal cycling, which was conducted on a subcomponent scale to mitigate risk during the development of the prototype.

FIBER SENSORS TECHNOLOGY IN BRIEF

In the next section, two types of optical fiber-based sensors are summarized, as well as a typical interrogator system used for structural health monitoring.

1. Fiber Bragg grating for structural health monitoring

Fiber Bragg gratings are periodic changes to the index of refraction, occurring in the core of the optical fiber. These periodic changes of refraction, accumulated together, lead to a strong reflection of a specific wavelength, also known as the *resonant wavelength*, of the grating. Equation (1) shows that the resonant wavelength is governed by the design:

$$\lambda_{FBG} = 2n_e\Lambda \tag{1}$$

where λ_{FBG} is the design wavelength of each FBG; and n_e is the effective index of refraction change in the single-mode fiber (usually a constant value); and Λ is the gap between each periodic refractive index change (or the pitch length). To fabricate these changes in the index of refraction, the fiber will be exposed to an ultraviolet (UV) laser light with a “zebra pattern” phase mask to produce the desired resonant wavelength.

The FBG when exposed to environmental perturbations such as mechanical strain or temperature change leads to a change in the pitch size, which causes changes in both coefficient of thermal expansion (CTE) and strain-optics coefficient [3]. Equation 2 shows the resulting wavelength shift:

$$\frac{\Delta\lambda_B}{\lambda_0} = (1-\rho_e)(\varepsilon_m + \alpha_{CTE}\Delta T) + \alpha_n\Delta T \tag{2}$$

where $\Delta\lambda_B = (\lambda_B - \lambda_0)$ is the delta change in Bragg wavelength due to environmental change; λ_0 is the initial Bragg wavelength of the FBG; ρ_e is the strain-optic coefficient (constant) of the FBG; ε_m is the mechanical strain based on the amount of length being stretched or compressed;

and α_{CTE} and α_n are the coefficient of thermal expansion and thermo-optic coefficient of the fiber core at room temperature, respectively. By monitoring the wavelengths of each FBG, the strain and temperature of the environment can be measured.

Since FBG is capable of measuring strain and temperature simultaneously, there is a need for an engineering effort to decouple the FBG sensors to measure temperature or strain, exclusively. For strain calculation, co-locating the temperature sensors are necessary to conduct the wavelength-shift offset caused by temperature change. For FBGs, which are utilized as temperature sensors that are bonded to a structure, the FBGs in question could be skewed as a result of the apparent strain to the structure. To alleviate the situation, the FBG sensors are placed unconstrained inside a hollow-core bonded tubing such that the sensors can experience temperature shift without incurring any strain.

2. Extrinsic Fabry-Perot Interferometer (EFPI)

The Extrinsic Fabry-Perot Interferometers (EFPI) takes advantage of the path length difference created from the gap between two highly reflective ends of a single-mode fiber. The EFPI is fabricated from bonding two separate ends of fiber optics within and onto a hollow-core extrinsic tubing, with a set gap-length, *l*, to create the path length difference. As light transitions from the optical fiber through an air gap, there is a partial reflection. The remaining light that travels through the air gap then interfaces with the second fiber which results in another partial reflection. The air gap distance causes a phase shift between the two reflected light waves, where the combination of constructive and destructive interference causes a fringe pattern. All of the reflected light will be collected from the photodetector (or *square-law detector*), where the light intensity is the square of both reflections. Equation (3) is as follows [4]:

$$I_r = |A_1 + A_2|^2 = {A_1}^2 + {A_2}^2 + 2A_1A_2cos\Delta\phi \tag{3}$$

When environmental perturbation occurs, the air gap in the middle of EFPI will change and that change leads to the fringe distance difference, where the effect is sinusoidal, as denoted by cos$\Delta\phi$. Accurate strain measurement can be achieved by monitoring the phase change in output fringes.

3. Fiber sensor data acquisition via wavelength division multiplexing (WDM)

Most fiber interrogation systems, also known as data acquisition systems (DASs), usually contain both the optical excitation light source as well as the receiving photodetector and the corresponding spectrum analyzer. Unlike a more complicated setup of optical frequency domain reflectometry (OFDR), where each FBG sensor is cascaded into the same fiber, cable is identified by a unique frequency, and signal processing (such as fast-Fourier transfer) is needed to decipher the combined signal. The wavelength division multiplexing (WDM) works by identifying the wavelength information of each unique sensor.

Figure 1 shows a typical setup for a DAS, using wavelength division multiplexing (WDM) technology. A light source, usually based on a broadband incoherent light, typically, a super-luminescent light-emitting diode, will provide light through the output port via a single-mode fiber – usually at C-band around 1550 nm. Each fiber Bragg grating (FBG) sensor contains a unique resonant wavelength ($FBG_{\lambda n}$) that acts as a notch filter, where the specific resonant wavelength will be reflected to the DAS unit, and the back-reflected light will be collected by an optical spectrum analyzer (OSA). A typical spectrum analyzer is built via free-space optics, where an optical-fiber-based collimator will direct the light into a specific diffraction grating and, for each unique wavelength, will be back-reflected into the detector (usually based on a charge-coupled device (CCD) camera array). The interrogation speed of the mentioned spectrum analyzer is dependent on the refresh rate of the CCD camera, and the bandwidth resolution is based on the number of CCD arrays available on the chipset as well as the reflecting distance from the diffraction grating. Typically, the resolution from a commercial broadband light-source-based WDM interrogator ranges up to approximately 1 picometer (pm); however, the trade-off for a detector-based WDM system hedges on the reliability of the bulk-optics components, specifically, on the deflection grating, where optical alignment problems caused by vibration can render inaccurate results from the system.

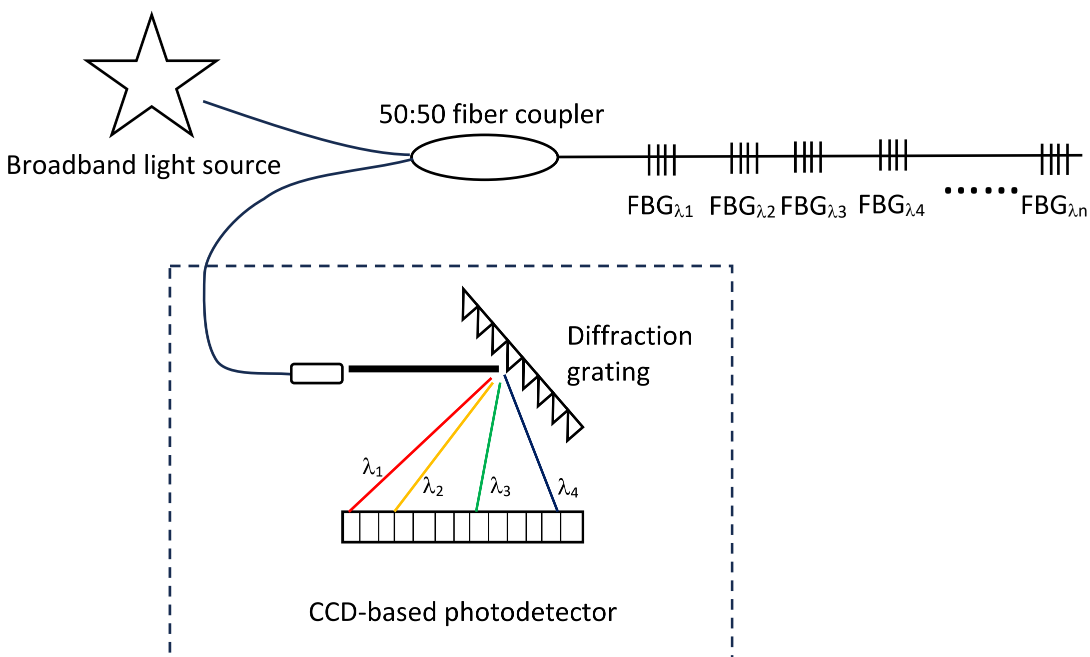

Figure 1. A typical wavelength division multiplexing (WDM)-based interrogator setup via a spectrum analyzer (dotted line) that is composed from a fiber collimator; a diffraction grating that separates each unique wavelength from each fiber Bragg grating (FBG); and a charge-coupled device (CCD)-based photodetector to read the wavelength from each FBG sensor.

NOVEL WAVELENGTH DIVISION MULTIPLEXING DATA ACQUISITION SYSTEM (WDM DAS) FOR RUGGEDIZED ENVIRONMENTS

The sections below will discuss a typical swept-source laser used in a fiber sensor interrogator, a novel laser that will be incorporated into this effort, and finally, the environmental testing that validates the potential benefits of utilizing this laser in aeronautics and beyond.

1. The swept tunable laser-based wavelength division multiplexing (WDM) interrogator

Another method of conducting WDM-based wavelength measurements is by utilizing a continuously swept tunable laser and mapping the reflecting signals via the photodetector. In practice, output of the sweeping laser gets stitched together, where the entire bandwidth being displayed is the starting and stopping wavelength of the swept laser. The acquisition speed, which utilizes this method of WDM interrogation, depends on the sweeping speed of the laser. Depending on the sweeping range and sweeping speed of the laser, the acquisition bandwidth can be tailored to what is needed; however, most of the commercially available, tunable laser-based WDM systems are using mechanically tunable lasers such as a mechanically tuned fiber Fabry-Perot tunable filter (FFP-TF) to control the wavelength of the fiber ring laser (Figure 2). The filter is tuned by adjusting the air gap between two fibers via a piezoelectric element that is bonded to one end of the fiber. Other mechanically tunable lasers use an external cavity laser, where the laser cavity includes free-space optics to induce laser sweeping via adjusting the laser cavity-length via a moving diffraction grating, which, in turn, changes the overall laser cavity length, thus changing the laser wavelength. Both the fiber ring laser setup and external cavity laser can be bulky in design, so integrating these components into an aerospace application could be complicated and may need mechanical isolation to achieve stability of the moving cavity. Discussed in this paper is an electronically tunable swept-source laser which is utilized to demonstrate a WDM DAS unit with no moving parts.

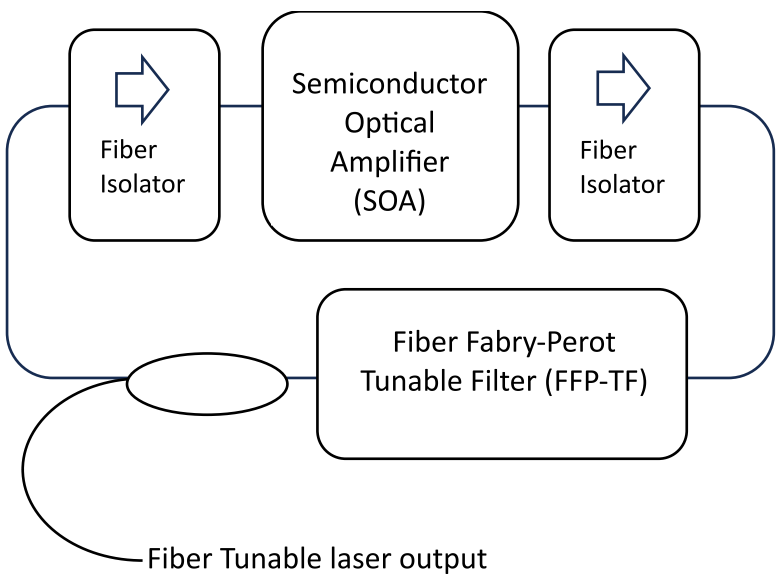

Figure 2. A mechanically tunable laser based on a fiber ring laser and a semiconductor optical amplifier (SOA).

2. Novel wavelength division multiplexing data acquisition system (WDM DAS) development

The tunable laser selected for a ruggedized WDM DAS is based on a version of a distributed Bragg reflector (DBR) laser, where the laser cavity waveguide is bounded by a Bragg mirror on one end, and an antireflective mirror on the other end. The DBR laser is widely tunable electronically by controlling the injection current of the laser gain cavity with no moving part.

Figure 3 shows an advanced version of the selected DBR laser based on a sampled grating distributed Bragg reflector (SG-DBR), where both ends of the laser cavity are fabricated with a Bragg reflector waveguide to act as a tunable mirror [5]. By adjusting the injection current from both mirrors as well as the dedicated phase control section and laser gain chip, a continuous wavelength-swept bandwidth is achievable with no moving parts from the laser unit.

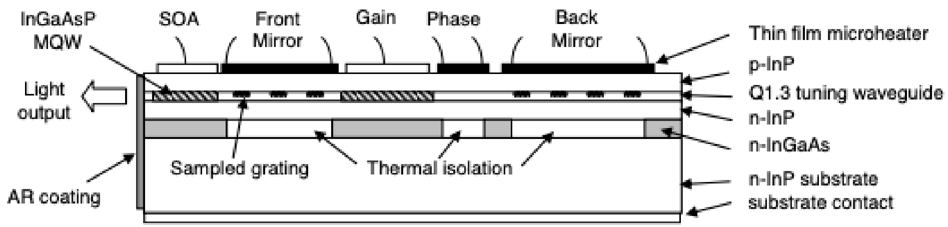

Figure. 3 A typical Sampled Grating Distributed Bragg Reflector (SG-DBR).

The laser is designed to have a center wavelength of 1550 nm, with up to 40 nm of sweeping range. The tuning resolution wavelength is 4 pm, and the tuning speed of the laser to complete the entire 40 nm of sweeping range is at 20 milliseconds (ms), which, in turn, translates the maximum sweeping speed to 50 Hz. Increasing the acquisition rate of the laser is possible by either sweeping a subset of the entire 40-nm range, or by skipping some sweeping ranges by sacrificing the tuning resolution (from 4 to 40 pm). A sweeping speed – up to 500 Hz – has been demonstrated in a laboratory unit. The incoming laser is then optically split into multiple channels via an optical coupler at a range of either 1 to 4 or 1 to 8, where each optical channel can have the full bandwidth available for sensor placement (FBGs and EFPIs). The returning signals are collected individually with a dedicated photodetector. The output of the photodetector is amplified by a transimpedance amplifier stage and then sampled by an analog-to-digital (ADC) converter.

Once all the channels have been recorded within the laser dwell time, the laser moves to the next wavelength to begin the process again. In practice, an 8-channel interrogator has been demonstrated. When each fiber channel is sampled by the ADC, a field-programmable gate array (FPGA)-based programmable central processor will collect the data, followed by an on-board microprocessor that will transmit the data via transmission control protocol (TCP) / user datagram protocol (UDP) via gigabit ethernet. A client computer receives the transmitted data and displays the output in real time. Figures 4 and 5 are the sample outputs, which show four individual channels interrogated at 50Hz, simultaneously, where two of the channels contain multiplexing FBG sensors and an EFPI sensor, respectively.

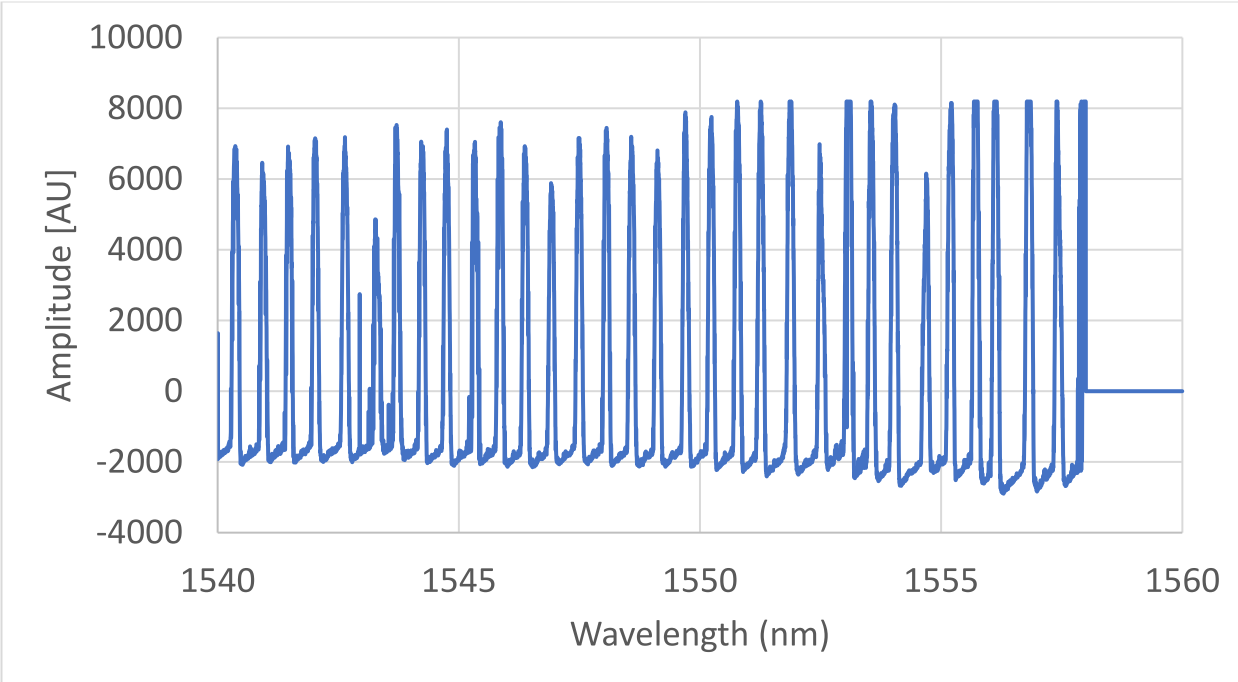

Figure 4. Output from the wavelength division multiplexing data acquisition system (WDM DAS) system with multiple fiber Bragg grating (FBG) sensors being captured simultaneously.

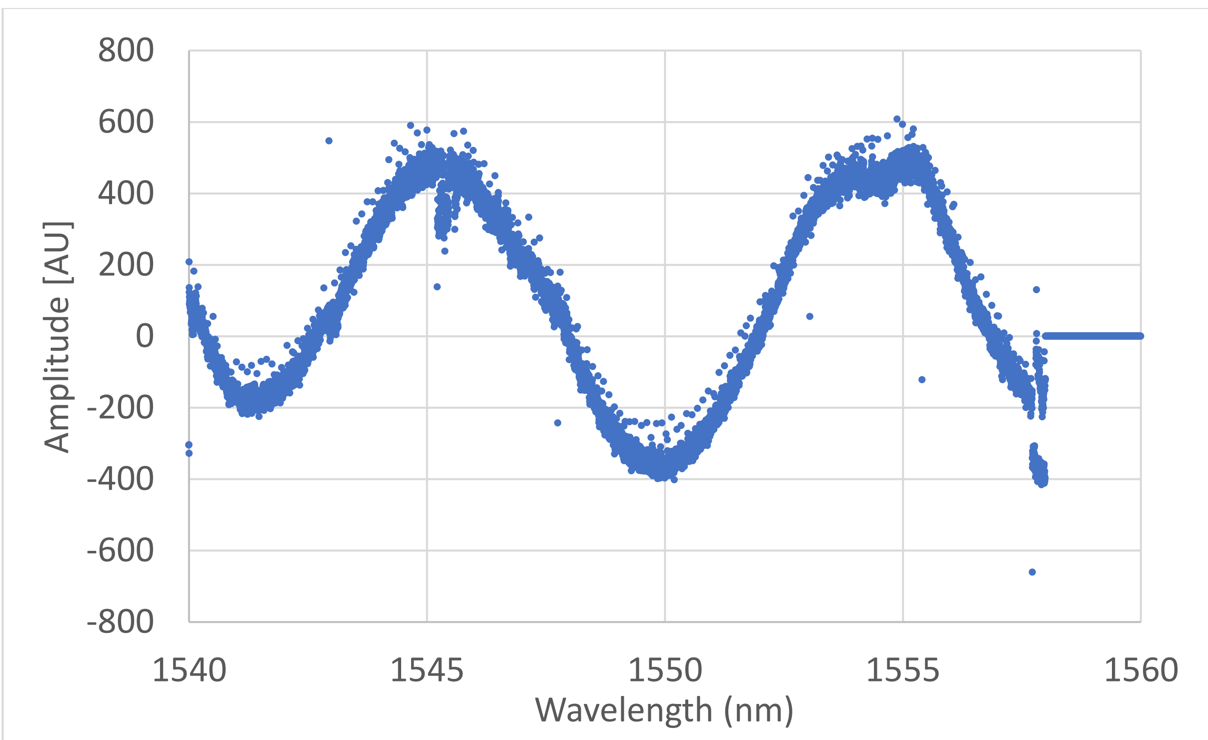

Figure 5. Output of an Extrinsic Fabry-Perot Interferometers (EFPI) sample captured from the wavelength division multiplexing data acquisition system (WDM DAS).

3. Environmental Testing of wavelength division multiplexing data acquisition system (WDM DAS)

To transition the WDM DAS from the laboratory to an aircraft, a set of environmental testing parameters has been selected. Figure 6 shows the spread-system version and schematics of the unit that were developed to undergo these tests in September 2022 at NASA AFRC. The spread system was developed such that each component was spread out on a base plate such that troubleshooting each subcomponent was possible.

The initial environmental testing that was conducted consisted of vibration testing that simulated a representative flight environment in all three axes of vibration with separate temperature and altitude testing conducted in a chamber, as shown in Figures 7 and 8, respectively. Three vibration profiles for all x, y, and z axes were conducted: 1) 5.3 root-mean-square acceleration (GRMS) at 10 minutes; 2) 6.3 GRMS at 10 minutes; and 3) 8.9 GRMS at 1 minute, and the WDM DAS remained functional throughout all vibration profiles with little or no system noise coming from vibration. A simulated temperature and altitude profile was also conducted with 15 minutes of dwell time at target altitudes. The system experienced a temperature change ranging from -40 to 122 ^{o}F of the operational limits as well as nonoperational limits ranging from -70 to 185 ^{o}F for one hour. The unit remained operational other than laser noise that was observed at -40 ^{o}F, where the laser was struggling to maintain its desired operating temperature. These environmental tests provided needed insight to better design an appropriate enclosure for the flight demonstration unit.

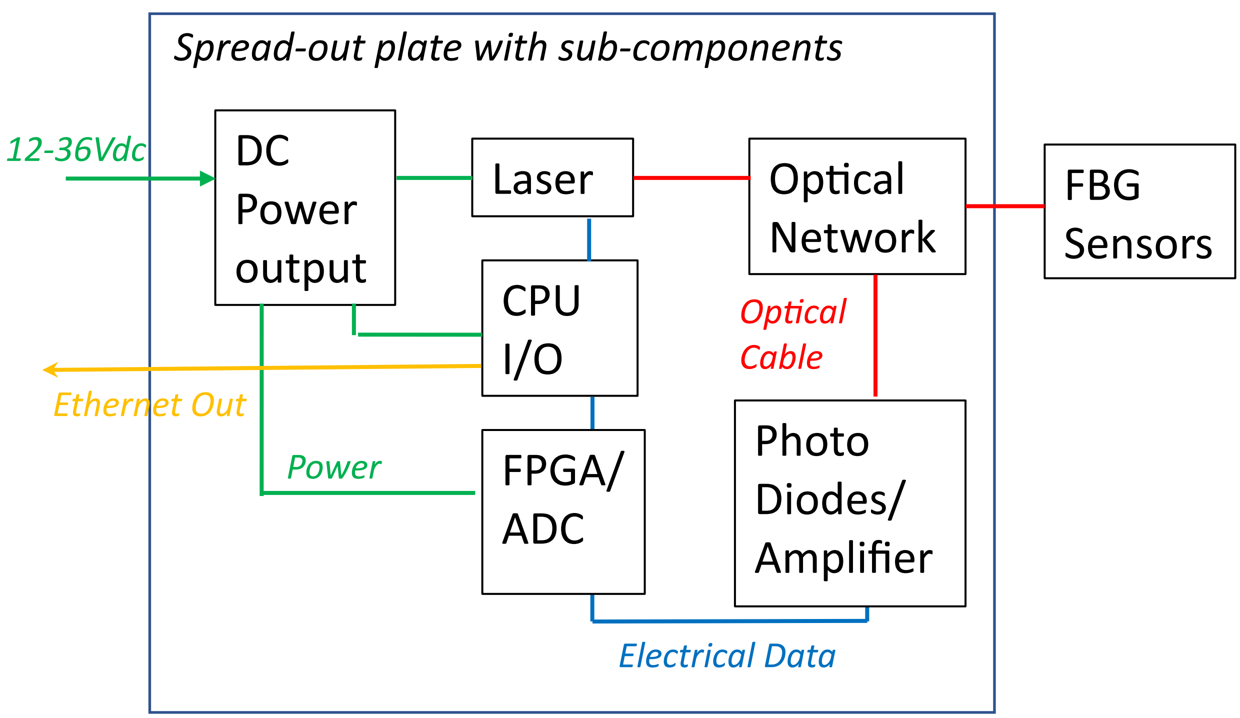

Figure 6. Schematics of a spread-system wavelength division multiplexing data acquisition system (WDM DAS) while undergoing environmental testing.

Figure 7. A Shaker table used for vibration testing at NASA AFRC.

Figure 8. A Thermal chamber used for temperature testing at NASA AFRC.

CONCLUSIONS

In summary, a novel wavelength division multiplexing data acquisition system (WDM DAS) has been developed by the National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (AFRC) that utilizes sampled grating distributed Bragg reflector (SG-DBR) lasing technology to take advantage of nonmoving parts and multiple channels with full-bandwidth design, which can be interrogated simultaneously and continuously via a novel analog switching method. Additionally, simulated environmental component testing provided the confidence that was needed towards the continuing pursuit of this technology. Currently, the DAS unit is under device integration with a target prototype dimension of 6.8 by 4.5 by 2.8 inches and 3.5 pounds. This prototype unit will undergo the same environmental testing as the component level, and a planned target deployment date is scheduled for late 2024.

REFERENCES

[1] Prosser, W. H., M. C., Wu, S. G. Allison, S. L. DeHaven, and A. Ghoshal, *Structural Health Monitoring Sensor Development at NASA Langley Research Center*, NASA/TM-2002-20040085739, January 2002.

[2] Wu, Meng-Chou, Winfree, William P., and Allison, Sidney G., "Fiber Optics Thermal Health Monitoring of Aerospace Structures and Materials," paper 7294-42, *SPIE Smart Structures/NDE 2009*, (San Diego, California), March 9-12, 2009.

[3] Chan, Hon Man, "Novel Fiber Optic Sensing Arrays with Enhanced Sensitivity in Cryogenic Temperatures," NASA/TM-20205009645, August 2021.

[4] Munns, Thomas E., et al., *Health Monitoring for Airframe Structural Characterization*, NASA/CR-2002-211428, February 2002.

[5] Larson, M.C., et al. "Narrow linewidth high power thermally tuned sampled-grating distributed Bragg reflector laser, *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013*, (Anaheim, California), paper OTh3l.4, March 17-21, 2013. (Available on-line at: https://opg.optica.org/abstract.cfm?URI=OFC-2013-OTh3I.4).