Optical Exhaust Gas Temperature (EGT) Sensor and Instrumentation for Gas Turbine Engines

Mehrdad Pakmehr, Joannes Costa, George Lu
optoXense, Inc.
San Ramon, CA 94583, USA

mp@optoxense.com

Alireza Behbahani
Air Force Research Laboratory
1950 Fifth St, Wright-Patterson AFB, OH, USA

alireza.behbahani@us.af.mil

ABSTRACT

This goal is to develop an inexpensive, robust, durable, and networkable EGT sensor and instrumentation for operation in the extreme temperature environments of aircraft gas turbine engines. The next generation of adaptive engines require low cost/weight and more robust instrumentation systems, controls, and PHM capabilities. EGT measurement in gas turbine engines is considered a key parameter for optimizing fuel economy and PHM systems. Currently, direct EGT measurements made on turbine modules are limited due to the ultra high temperature (UHT) environment. Accurate EGT measurements and durable sensors are of specific importance for high performance military turbine engines. A new FBG-based EGT sensor system is presented which involves fiber optic sensing technology developed for operation in UHT conditions using sapphire fibers instead of the silica fibers to raise the operating temperatures to 1600°C. Instrumentation development process includes: (a) producing a minimally intrusive EGT sensor based on silica fibers but with UHT housing materials to account for actual deployment conditions, (b) demonstrating a development path to prove viability of FBG temperature sensing with sapphire fibers, (c) conducting laboratory tests and verification, and (d) developing a plan for engine test cell experiments. Sensor ruggedness, precision, accuracy, and frequency response in a representative environment will be studied. This optical EGT sensing system enables robust sensing in both legacy and next generation engines used on military and commercial aircraft.

Key Words:

Sensor, Engine Instrumentation, Exhaust gas temperature (EGT), Turbine engine, control, PHM, Ultra high temperature (UHT), Fiber optics sensing, Fiber Bragg grating (FBG)

1.0 INTRODUCTION

The exhaust gas temperature (EGT) is defined as the gas temperature at the exit of the turbine; the sensors used to measure this parameter are considered the most vulnerable elements of the entire turbine engine instrumentation. EGT measurement is needed for optimizing fuel economy, diagnosis, and prognosis. The reason is that turbine blade temperature is a good indicator for normal life consumption of that blade [1]. Currently, direct sensor measurements made on turbine modules are limited due to the ultra high temperature (UHT) environment. EGT sensors located downstream from the highest temperature sections provide a means to roughly infer the temperatures seen by the turbine blades/disks. But these sensors, which themselves are subject to frequent failures, provide a fairly inaccurate indication of the actual metal temperature profiles. Accurate EGT measurements with durable sensors are of specific importance for high performance military turbine engines where the margin between hot section operating conditions and material limitations is shrinking [1].

EGT and other turbine temperature sensors are susceptible to degradation due to high temperature oxidation, erosion and contaminant intrusion into probes and wiring harnesses. Thermocouples are easily affected by noise, electromagnetic interference, and/or other environmental factors. Military and commercial field experience indicates that gas path thermocouple removals affect aircraft availability and add maintenance time. Also, the adaptive engines of the future are driving the control system to outperform legacy design, and cause higher temperatures.

Existing technologies for measuring EGT typically implement high temperature capability with thermocouples but extension to higher temperatures is not guaranteed. Other technologies that have been investigated include thin film thermocouples, pyrometers, spectroscopy, and radioactive isotope-based sensors [1]. They are not mature, accurate nor cost-effective for engine implementation. In addition to being not mature, multicolor pyrometers are also complex, emissivity dependent, and expensive [1]. With alternate technologies that use fiber optic technology [2][3][4][5][6][7] to measure exhaust gas effects, measurement of significantly higher temperatures is possible for EGT sensing.

Fiber optic and laser-based sensing systems [2][3][4][5][6][7] are envisioned to be used for EGT measurement and to accurately assess the condition and life usage of the turbine engine hot section, on a blade-by-blade basis. To understand the extreme environmental conditions experienced in turbine engines, there is a need for robust sensors to obtain high precision EGT measurements. The main objective of this work is to develop a new technology for reliable EGT measurement using optical fibers in future high performance turbine engines. The control and health management of modern turbine engines depends on sensing a wide variety of quantities throughout the engine, (e.g., temperatures, pressures, and vibration, etc.) with different redundancy, reliability, and accuracy requirements; reliable EGT measurement is one of the challenges for gas turbine engine control and health management improvement.

An optical sensor system extends gas temperature measurement capability in turbine engines [8] beyond the present generation of EGT sensing technologies. The sensing element which consists of fiber Bragg gratings (FBGs) embedded inside a sapphire lightguide is capable of operating in UHT conditions. The sensor generates an optical signal as a function of temperature. An optically averaged EGT measurement system can be developed by combining the optical signals from multiple individual sensing probes at a single detector assembly.

Military turbine engines require the following specifications for EGT sensing system:

(a) Best entitlement for accuracy at higher than experience range 9~12°C (12°C temp margin ~1% thrust margin) allotment in redline stack is required;

(b) It should survive the harsh environment while maintaining reliability, accuracy, ruggedness, and minimum size/weight/power;

(c) As aircraft turbine engines continue to push the envelope on material capabilities, it is important to create the capability of sensing close to the material limits for the operational turbine system;

(d) It should be able to survive the expected life of the engine between overhauls and measure temperatures in excess of 1600°C (Life: 2000 Engine Flight Hours (EFH), immersive - 4000 EFH, non-immersive);

(e) The accuracy of the sensing system should be 0.5% of full scale and stable over the life of the engine;

(f) Air temperature measurements in the exhaust gases must be taken outside of the wall boundary layer;

(g) It should be ruggedized for installation in production aircraft.

To address these needs, a new FBG based EGT sensor system is needed, which involves optical fiber sensing technology developed for operation in UHT conditions using sapphire fibers instead of the more common silica fibers. This will raise the operating temperatures from ~1000°C to ~1600°C. The development is a three-step process. First, since sapphire based optical sensors have yet to be reduced to practice, we will produce a minimally intrusive EGT sensor design based on silica fibers but with UHT housing materials, to account for actual deployment conditions. Second, as FBG sensors inherently perform better under single mode conditions while typical sapphire fibers are multimode conduits, as well as the fact sapphire fiber segments need to be kept short for optomechanical and cost reasons, we will demonstrate a development path to prove FBG temperature sensors embedded in sapphire fibers is indeed viable. Third, in addition to laboratory tests and verification, optoXense will develop a practical plan for engine test cell experiments, and a development path for commercial application of the technology. We will also plan to demonstrate the sensor ruggedness, precision, accuracy, and frequency response in a UHT environment at representative engine test facilities.

2.0 OPTICAL EGT SENSOR DEVELOPMENT

2.1 Technology tradeoff studies

The requirements and specifications of the sensor include: (a) sensor size, material, and specifications for design and fabrication; (b) optical sensors positioning and installation process; (c) a plan for test and verification of the sensor system at an engine test cell.

The tradeoff study for various high temperature optical fibers and protective materials is performed to select the fiber type, high temperature protective material type, and also various fiber coating options. The following tables provide information on fiber type, high temperature protective material type, and also various fiber coating options. Table 1 is a preliminary comparison of two high temperature fibers which can be used for the tradeoff study.

Fiber optic sensors need to interact with the environment if one wants to achieve a certain level of sensitivity to the measured parameter of interest. They should ideally also survive the lifetime of the monitored system. Particular care needs to be taken to provide the sensor and the fiber leads with adequate packaging and protection. A fiber optic sensor probe typically consists of different components and materials, including an optical fiber, special coating materials or chemical reagents, dedicated adhesives, filter or reflective elements, etc. This complicates the assessment of the reliability as all the different sub-parts of the sensor probe should be thoroughly evaluated. Additionally, fiber sensors are often used in harsh and very specific conditions.

Table 1: Comparison of ultra high temperature fiber sensor technologies

Optical Fiber Technology	Advantages	Disadvantages	Comments
Silica fiber (with 193 nm or 800 nm laser light)	- Flexible fiber supporting multiple sensor points. - Could be excellent for lead-in fiber attached to sapphire probe for highest temperatures	Limited to ~1000°C	This is the most mature high temperature fiber sensor technology. optoXense staff has demonstrated technology working to 1000°C for fiber alone.
Sapphire fiber	- Sapphire fiber has a melting point of ~2050°C. -Demonstrated to ~1400°C long term -Multimode fiber but adaptable for the proposed sensor system	When different modes are excited there will be an extra phase shifting for the modulated light, which will cause measurement error.	Stephen Mihailov has fabricated multiplexed FBGs in sapphire fiber using an 800 nm femtosecond pulse laser [9][10].

The durability and reliability in long term service is not guaranteed by just conducting acceptance tests. In this respect, more research is required to understand failure mechanisms and for estimating those parameters that are essential to long term functionality. Interfacial parameters such as normal stress, friction, and decohesion energy of fiber/coating or coating/embedding matrix are important for the stress transfer to the sensor. There is no lifetime model available neither for embedded fiber sensors under load, nor for specially coated fibers that face long term exposures to a variety of chemicals. High temperature is especially an issue for fiber optic sensing in gas turbine engine.

Table 2: Laser writing procedures for optical fibers and FBGs

Option	Annealing	Description	Comments	Ref.
Type I-UV	No	Writing with a typically at 248 nm (KrF) or 193 nm (ArF), but also IR at 800 nm with hydrogen loading and lower laser intensities	FBG reflectivity can decrease above 250°C with complete erasure above 800°C.	[11][12]
	Yes		FBG can be regenerated so that it is stable at 1000°C	[13]
Type II-UV		Writing with a high power pulsed UV laser	Pulsed writing results in period compaction – Effect on strength vs Type I to be evaluated	[14]
UHT-IR		Writing with an ultrafast high power pulsed IR laser	Sensor theoretically robust to 1750°C	[14]

FBG reliability and durability highly depend on the manufacturing procedure in which there can be considerable variation by different developers and manufacturers. Those that are manufactured optimally will be much stronger than those that are not. Nevertheless, there are tradeoffs. These tradeoffs could be evaluated/tested during our sensor design and analysis. Table 2 and Table 3 show some preliminary considerations for design and analysis based on the fiber manufacturing methods and the various available technology options.

Table 3: Fiber coatings procedures

Option	Option Name	Description	Comments
Option 1	Strip & recoat	Strip buffer layer, inscribe FBG, recoat (Chemical vs. mechanical stripping)	Fiber can be damaged during stripping, recoat is not as robust as original coating. In the early days the buffer layer was removed mechanically with microcracks resulting thus considerably weakening the FBG region.
Option 2	Write through	FBG inscribed through polyimide buffer layer without removing it	Reflectivity is generally lower than after writing without buffer layer. Not applicable to thicker acrylate buffer layers
Option 3	Draw tower	FBG inscribed as fiber being drawn before buffer layer coating applied	Fiber is moving, so inscription must be rapid; precision not as good as Option 1.

Whenever a drift of the EGT sensor data is observed the question has to be answered if the aging of the used sensors, or the instrument causes the drift. Proper sensor applications do not only require the monitoring of the sensor signals per se, but also condition monitoring of the environment, the sensors, and the sensor system. Self-diagnosis allows to discriminate between a possible permanent degradation of the sensor, a failure of the monitoring system, or the optical fibers, or a reversible short term loss in signal reliability due to environmental influences.

2.2 Design, fabricate, and characterize proof-of-concept optical EGT sensor

The goal is to develop a durable and high precision sensor suite. The sensor suite will consist of optical EGT sensor elements. One of the important goals is to develop high precision durable EGT sensor system that can operate in turbine engine UHT sections.

The design process focuses on functionality in UHT environment, durability, and robustness of the sensor system. Moreover, our approach adds multiplexed sensors and the ability to: (a) develop a nonintrusive installation process for the measurement system, (b) have a high precision and robust sensing system, and (c) make measurements at multiple points in UHT gas turbine engine environments without extensive harnessing requirements.

Figure 1 and Figure 2 provide simplified schematics of the developed EGT sensor probe. This is a proof-of-concept optical sensor system.

UHT fiber optic temperature probe design

Figure 1 shows a minimally intrusive EGT sensor core design based on silica fibers, though we will be using UHT probe housing materials to account for actual deployment conditions for the mechanics.

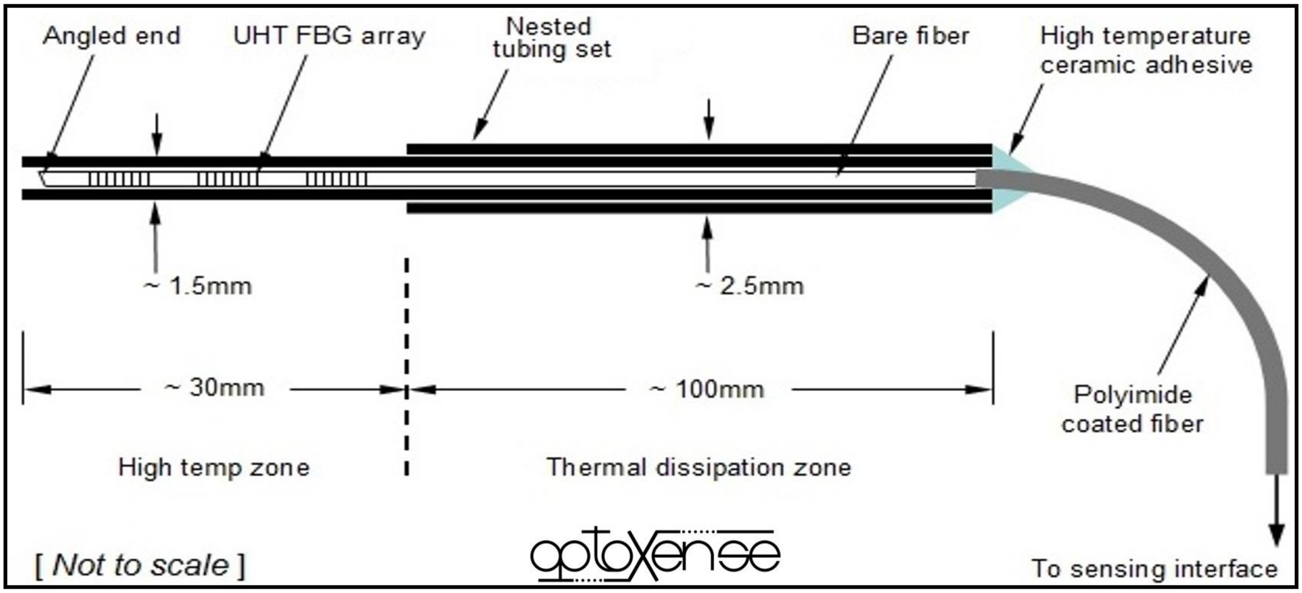

Figure 1: UHT fiber optic probe body design.

The photonics goal is to push the standard silica based FBG sensors to their limits and beyond. The mechanical goal is to minimize physical space impact for the UHT section of the probe, while providing enough probe body for handling, mechanical mounting, and thermal dissipation outside of the UHT zone, and to confirm the structure will survive the anticipated 1600°C operating conditions. We emphasize the "core" designation, because in practice this element may not be deployed as is, but rather inserted into appropriate sensor acceptance ports designed for production processes and maintenance routines.

The main features of the sensor core are as follows:

- The design aspect ratio of the probe body is 52:1, based on its largest diameter.
- The probe housing material limits (ceramic ~2200°C) will suffice for this exercise.
- The angled end of the fiber is to diminish the effect of spurious reflected signals and resonances which will impact FBG signal response analyses.
- The fiber end containing the sensor array is free to experience thermal expansion and contraction, thereby decoupling mechanical strain effects from the sensor array's thermal response.

Limited distance sapphire FBG sensor studies

As noted previously, there are several concerns related to the optical viability of generating well defined FBG response signals. Our response is to go back to fundamentals and initiate a different path for reduction to practice, especially with the specific application in mind – minimally intrusive UHT sensors for turbine engines, where a significant propagation length does not yield an appreciable advantage since the sensor portions need to be small. The basic experimental setup is shown in Figure 2.

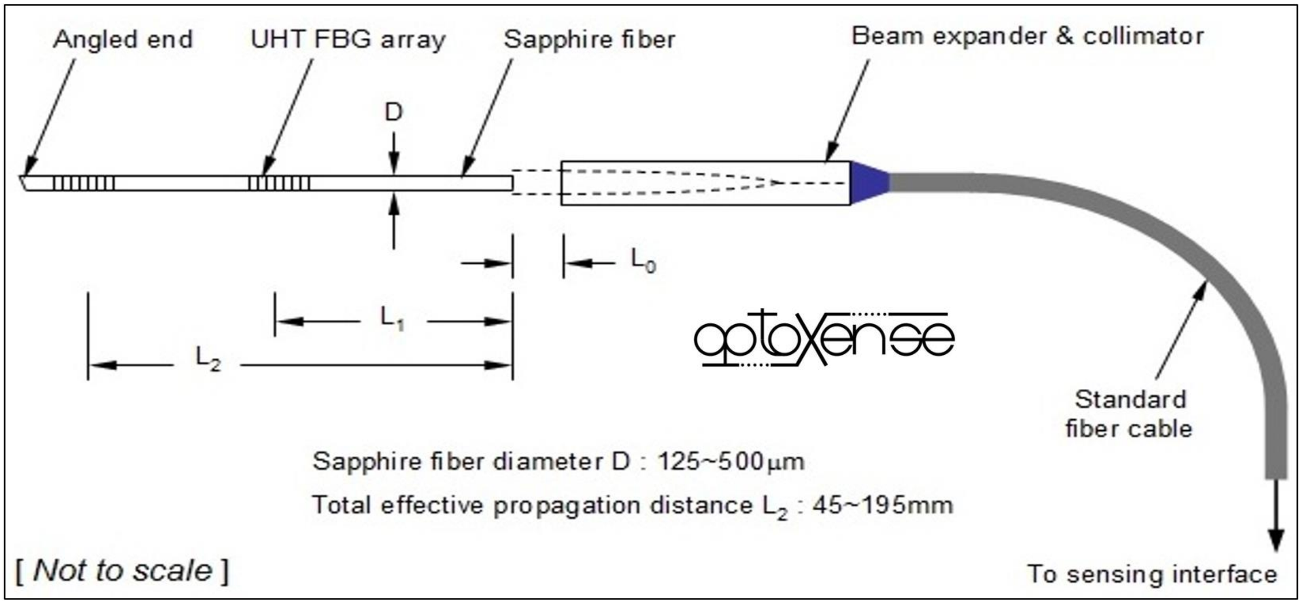

Figure 2: Sapphire FBG parameter effect setup.

Although this is a room temperature evaluation, we will still employ UHT FBG elements within the sapphire fiber, to avoid inconsistencies in future experiments based on this initial work.

Most sapphire fibers do not have a round cross section, but rather a rounded hexagonal shape. The material is uniaxial. And the surfaces are not perfectly smooth. Therefore, we start by introducing collimated light into the sapphire fiber, which will minimize the generation of large angle light rays and minimize scattering losses. Note that "collimated" is a relative term. Given the wavelength, aperture size, beam size, and the associated optical collimation component performance limits based on these parameters, the light rays incident on, and propagating through, the sapphire fiber will not all be perfectly parallel. To address this, the input gap distance L_0 between the collimator output and fiber input will be adjusted for optimum response in terms of sensor signal selectivity and minimal noise.

We will then fix the sensor response wavelength (e.g. 1540 and 1550nm) and examine the primary parameters – diameter D and propagation distance L_x – against FBG signal response characteristics. After data for optimum L_0 has been documented, response degradation vs. L_0 can be examined.

2.3 Evaluation and verification of the EGT sensor in the laboratory environment

For the first step of *calibration*, we concentrate on the static calibration. Since the device has to survive the tests, and for this stage of the development the FBG elements are hosted in silica, the low to midrange temperature zone (25~800°C) will be examined in detail first. After an initial scan of the overall FBG response vs. temperature plot, we will further define additional temperature regions with higher resolution increments to highlight any nonlinearities or perturbation features in the calibration plot. Each temperature point will require a thermal stabilization timeframe for the oven, which in turn will anneal the elements at those particular temperature points, and after further time to allow settling of the FBG response this will also yield *short term drift* data. Before moving onto the higher temperature regions (>800°C), a basic *hysteresis* evaluation will be performed by reversing the test path towards lower temperature points. Then on the cycle back up, the high point of the midrange (i.e. 800°C) can be used for a *longer term drift* test. Finally, at the higher temperatures we expect the array to yield a linear calibration response, and we further expect to observe the point at which the FBG signal levels start to decrease due to the higher temperatures affecting the permanence of the FBG elements within their silica host. This irreversible constraint, indigenous to this work, is why the majority of the sensor calibration and evaluation processes needs to be demonstrated at the low to midrange temperature zone. Temperatures beyond the FBG response limit will be used solely for sensor housing survival studies. We will conduct dynamic sensor response studies (e.g. transient heating using a focused high power pulsed laser beam) and engine test cell evaluations in near future.

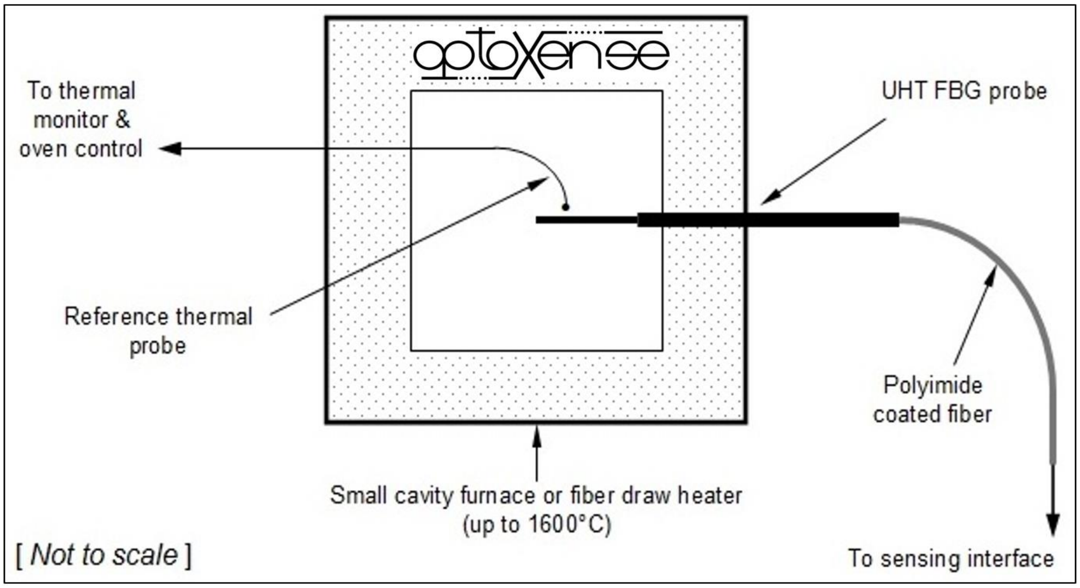

Figure 3: UHT EGT fiberoptic probe response setup for static calibration.

High temperature oven tests: Temperature tests will be done using a small cavity UHT oven, as shown in Figure 3. As example of such a UHT unit is the FIB-THM500 fiber heater by Micropyretics Heaters International. Static incremental temperature points will be defined to establish a wavelength vs. temperature calibration profile, to demonstrate overall temperature performance. More specific results will be mechanical survival of the housing, and any impact on data integrity. We expect to witness the failure of the FBG gratings due to the limited operating temperature of their silica host.

Frequency response test setup design: An experimental test setup is developed and shown in Figure 4 for testing the frequency response of the proposed EGT sensing system. The heat source is an 830nm diode laser capable of 2W maximum optical power (e.g. ThorLabs LB830ME2W), and a fast laser driver (e.g. Highland D200), to get up to 100 kHz laser modulation rates with adjustable duty cycles. The laser emitter is typically 1 µm x 100 µm, and can be imaged onto the FBG to a new extent of 10 µm x 1000 µm, thus achieving up to 20 kW/cm^2 peak intensities. This should be enough to yield good S/N during FBG temperature response tests.

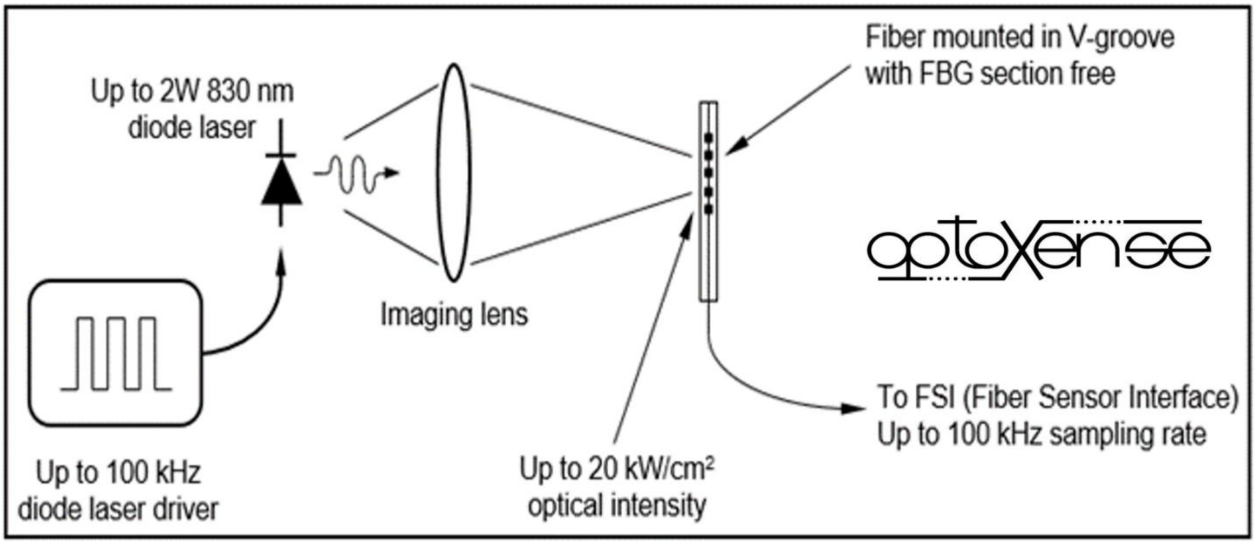

Figure 4: High frequency, high intensity optical test setup to evaluate the thermal response time of an FBG temperature sensor.

3.0 CONCLUSION

Currently, direct EGT measurements made on turbine modules are limited due to the ultra high temperature (UHT) environment. Accurate EGT measurements and durable sensors are of specific importance for high performance military turbine engines. A new FBG-based EGT sensor system development is presented here which involves fiber optic sensing technology developed for operation in UHT conditions using sapphire fibers instead of the silica fibers to raise the operating temperatures to 1600°C. This work produces a minimally intrusive EGT sensor based on silica fibers but with UHT housing materials to account for actual deployment conditions, as the first step to demonstrate viability of FBG temperature sensing with sapphire fibers. This is an ongoing work, currently we plan to conduct laboratory tests and verification, and then to conduct engine test cell experiments. Sensor ruggedness, precision, accuracy, and frequency response in a representative environment will be studied. This optical EGT sensing system enables robust sensing in both legacy and next generation engines used on military and commercial aircraft. This technology is not only applicable for military engines, but also for commercial aircraft and automobile engines.

REFRENCES

[1] A. Von Moll, A. Behbahani, GC Fralick, JD Wrbanek, GW Hunter, "A Review of Exhaust Gas Temperature Sensing Techniques for Modern Turbine Engine Controls," 50th AIAA JPC, Cleveland, OH, July 2014.

[2] Tregay, G., Calabrese, P., Finney, M., Stukey, K., "Durable Fiber-Optic Sensor for Gas Temperature Measurement in the Hot Section of Turbine Engines," SPIE Vol. 2295 Fly-by-Light, 1994.

[3] M. Willsch, T. Bosselmann, P. Flohr, et. al, "Design of Fiber Optical High Temperature Sensors for Gas Turbine Monitoring," Proc. SPIE 7503, 20th Intern. Conf. on Optical Fibre Sensors, 75037R, Oct 5, 2009.

[4] Hua Xia, Doug Byrd, Sachin Dekate, and Boon Lee, "High-Density Fiber Optical Sensor and Instrumentation for Gas Turbine Operation Condition Monitoring," Journal of Sensors, Vol. 2013, 2013.

[5] D. Grobnic, S. J. Mihailov, C.W. Smelser, and H. Ding, "Sapphire Fiber Bragg Grating Sensor made using Femosecond Laser Radiation for Ultrahigh Temperature Applications," IEEE Photonics Technology Letters, Vol 16, No. 11, pp. 2505-2507, 2004.

[6] A. Wang, H. Xiao, J. Wang, Z. Wang, W. Zhao, R. G. May, "Self-Calibrated Interferometric-Intensity-Based Optical Fiber Sensors,". Journal of Lightwave Technology, Vol 19, No. 10, pp. 1495-1501, 2001.

[7] M. Gottlieb and G. B. Brandt, "Fiber-Optic Temperature Sensor Based on Internally Generated Thermal Radiation," Applied Optics, No. 19, Vol. 20, pp. 3408-3414, 1981.

[8] M. Pakmehr, J. Costa, A. Behbahani, et. al, "A Review of Fiber Optic Networks for Turbine Engine Instrumentation Channel: Control, PHM, and Test Cell Applications," 50th AIAA Joint Propulsion Conference, Cleveland, OH, 2014.

[9] S.J. Mihailov, D. Grobnic, and C.W. Smelser, High temperature multiparameter sensor based on sapphire fiber Bragg gratings," Optics Letters **35**(16), 2810-2812, August 15, 2010

[10] S.J. Mihailov, "Fiber Bragg Grating Sensors for Harsh Environments," *Sensors* 12, 1898-1918, 2012.

[11] C. W. Smelser, D. Grobnic, S. J. Mihailov, "High Temperature Stable Fiber Bragg Gratings in hydrogen loaded all-silica core fiber," OSA/FiO/LS/AO/AIOM/COSI/LM/SRS 2009, Paper FTuD7.

[12] K. O. Hill and G. Meltz, "Fiber Bragg Grating Technology: Fundamentals and Overview," JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 15, NO. 8, 1263-76, AUGUST 1997.

[13] J. Canning, "Regenerated Gratings for Optical Sensing in Harsh Environments," Advanced Photonics Congress, Paper BTu3E.3, 2012 OSA

[14] J. L. Archambault et al, "Type II FBGs," Electron. Lett., Vol. 29, 1993, p. 453.