Fast fiber Bragg grating interrogation system with scalability to support monitoring of large structures in harsh environments

Behzad Moslehi, Richard J. Black, Joannes M. Costa, Elizabeth H. Edwards, Fereydoun Faridian
and Vahid Sotoudeh
Intelligent Fiber Optic Systems Corporation (IFOS)
2363 Calle del Mundo, Santa Clara, CA 95054-1008

ABSTRACT

Fiber optic sensor systems can alleviate certain challenges faced by electronics sensors faced when monitoring structures subject to marine and other harsh environments. Challenges in implementation of such systems include scalability, interconnection and cabling. We describe a fiber Bragg grating (FBG) sensor system architecture based that is scalable to support over 1000 electromagnetic interference immune sensors at high sampling rates for harsh environment applications. A key enabler is a high performance FBG interrogator supporting subsection sampling rates ranging from kHz to MHz. Results are presented for fast dynamic switching between multiple structural sections and the use of this sensing system for dynamic load monitoring as well as the potential for acoustic emission and ultrasonic monitoring on materials ranging from aluminum and composites to concrete subject to severe environments.

Keywords: Fiber Optic Sensors; Optical Interrogation; Fiber Bragg Grating (FBGs); FBG interrogation

1. INTRODUCTION

Optical fiber sensor systems are increasingly delivering new and effective measurements in manifold applications benefiting from optical fiber properties given in Table 1.

Table 1. Properties and benefits of optical fibers

Property	Example Application / Benefit / Importance
Electromagnetic interference (EMI) immunity	Many applications such as those involving high EM environments in naval and aerospace systems
EMI passivity / no electronic footprint of sensing fiber	Security and when dealing with systems susceptible to EMI
Electrical passivity	Safety in explosive environments
Light-in-weight	Aerospace / lighter payloads
High durability with appropriate installation and/or packaging	Capable of surviving and operating in extreme temperatures (e.g., 5 - 1200 K), pressures and high radiation environment
Small-in-diameter, minimally intrusive, flexible	Applications requiring access through minimum diameter holes, e.g., keyhole surgery
Low-loss and capability for distributed sensing over long lengths (kilometers) of a single fiber	Enables transmission over long distances (many kilometers) so that the sensors can be remote from the instrumentation
Relatively easy to install multiple sensors	Many sensors can be place on a single fiber “wire” rather than multiple wires being required for each sensor.

Fiber Bragg Gratings (FBGs)[1] form the prime example of a sensor element that lends itself to multiplexing of many sensors along a single optical fiber for measurement of static and dynamic strain[2] as well as temperature[3, 4] and derivative properties, given the appropriate packaging/transduction, such as acceleration and pressure[5]. FBG sensing systems are being deployed in a wide variety of structural health monitoring applications (SHM)[6-12] with the measurement of parameters such as strain, temperature, fracture, vibration or simultaneously sensing multiple parameters. Diverse applications include aerospace[6, 7, 13], robotics[14], nuclear reactors[15], wind turbines[15], concrete structures[16], bridges[9, 11] MRI compatible medical devices[17, 18], oil & gas [19-22] and geothermal wells[23].

A key enabler that distinguishes different end-to-end FBG sensor systems[3, 24] is the FBG interrogation instrumentation[25]. An FBG interrogator supports FBGs that can (a) form multiple sensors on one or multiple optical fibers simultaneously through wavelength division and other multiplexing techniques, (b) through measurement of characteristic wavelengths, provide information regarding the dynamic strain and temperature (or derivative measurands) seen by the FBGs, and (c) provide a basis for monitoring structural health state.

The remainder of this paper is organized as follows. In Section 2, we introduce the IFOS fast, high sensor count FBG interrogation system. In Section 3, we discuss calibration for converting wavelength change to strain and temperature and quasi-DC measurements. In Section 4, we discuss low to mid frequency (kHz) measurements. In Section 5, we discuss some example high frequency measurements and in Section 6, we conclude.

2. FAST HIGH SENSOR COUNT FBG INTERRROGATION SYSTEM

In Figure 1, we show the IFOS FBG interrogation network with a scalable architecture for supporting 1024 FBG sensors based on multiple interrogation units with each unit supporting up to 128 sensors distributed among 4 fibers with 32 sensors on each fiber. These numbers assume a reasonable strain range, and in fact more sensors, e.g., double could be supported for a smaller range. Rather than going to 1000 or more sensors on a single fiber using a frequency division multiplexing approach but entailing speed and precision limitations, we have opted for a 1000-sensor network built up with multiple fibers each having a moderate number of sensors using a combination of multiplexing techniques (including wavelength and space division) to provide high precision with the option of high sampling rates. Each band or subgroup of sensors can be interrogated simultaneously at up to MHz rates, although for reduced electronics cost, configurations with lower sampling rates may be chosen, e.g., our base unit operates at 6 kHz.

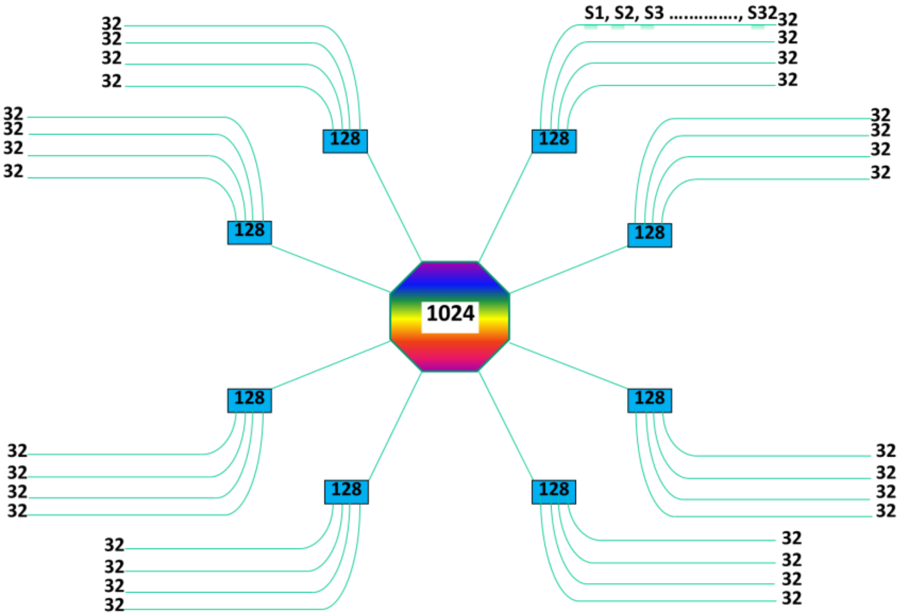

Figure 1. Scalable architecture supporting 1024 sensor based on interrogator nodes (Figure 2) supporting 128-sensors assuming a strain range of ±1500 µstrain and 4 wavelength bands (totaling ~154 nm).

Figure 2 provides a functional schematic of an interrogation node, which supports up to 128 sensors for a moderate strain level (±1500 µstrain) or up to 256 sensors for smaller ranges (±500 µstrain allowing for enough separation between FBG wavelength bands to avoid appreciable cross-talk) as detailed in Figure 3. Each interrogation unit supports kHz switching between 4 fibers. Note that Figure 2 is a functional diagram only and is neither to scale nor representative of the actual 3D physical positions of the subsystems. Current IFOS interrogation systems range from 50 to 80 cubic inches with the next generation planned to be iPhone size.

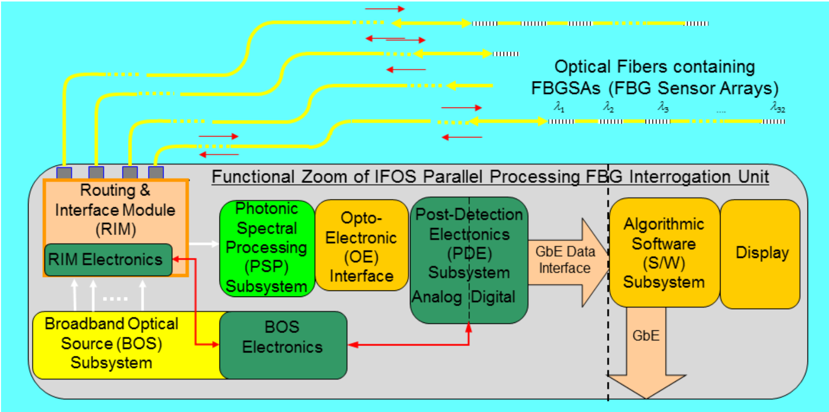

Figure 2. Functional schematic of building block interrogation unit including photonic, electronic and software/firmware subsystems and modules.

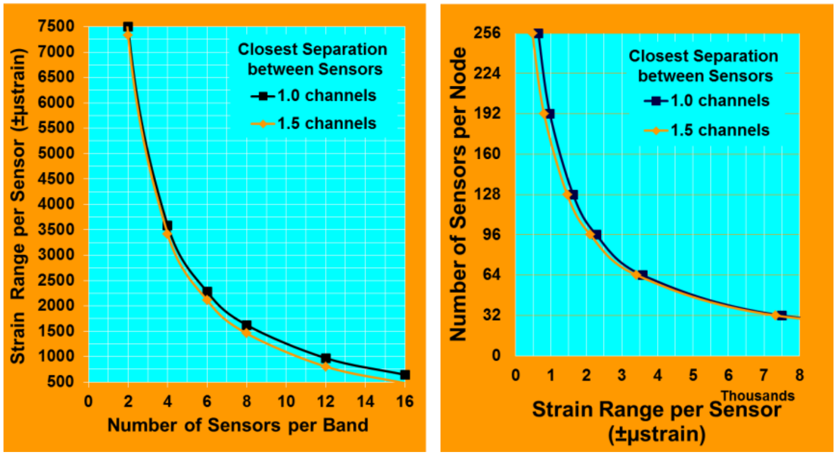

Figure 3. Number of sensors supported dependent on strain range given when each wavelength band is divided into 48 channels separated by approximately 0.8 nm: (a) ± strain range per sensor as a function of number of sensors per wavelength band. (b) Number of sensors per interrogation node as a function of ± strain range per sensor.

3. QUASI-STATIC MEASUREMENTS AND CALIBRATION

FBG interrogators can be used for measuring wavelengths to sub-picometer levels (with wavelength resolutions to between 10 and 100 femtometers) resulting in quasi-static strains level measurements to sub-microstrain order and temperatures to better than a tenth of a degree Celsius when only strain or temperature change is present. As seen in the examples of Figure 4, the fractional wavelength change is, to a good approximation, a linear function of strain, but has a slightly nonlinear dependence on temperature.

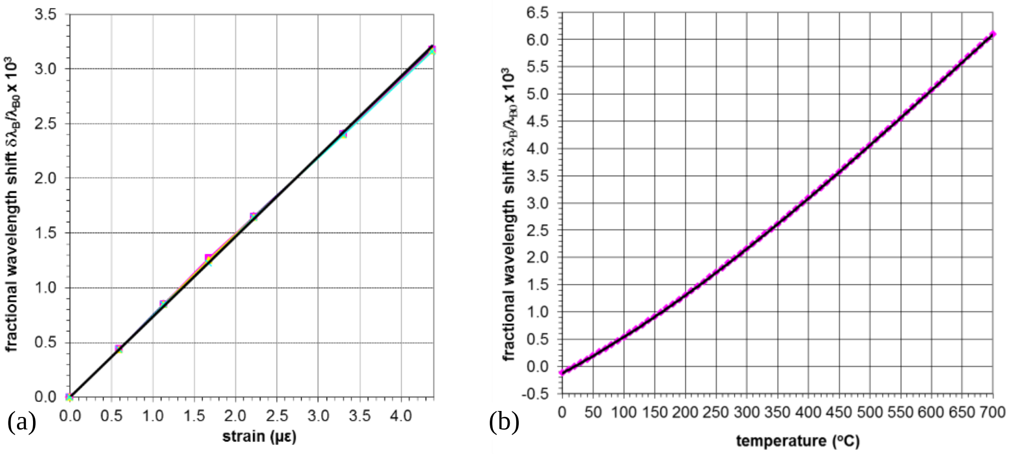

Figure 4. (a) Fractional wavelength shift versus strain (linear dependence). (b) Fractional wavelength shift versus temperature (slightly nonlinear dependence).

4. LOW TO MID FREQUENCY MEASUREMENTS

Figure 5(a) shows monitoring of an oscillating cantilever beam with an interrogation unit capable of supporting 128 to 256 sensors. Figure 5(b) shows an example graphical user interface (GUI) based on dividing the wavelength spectrum into 48 channels (upper plot) from which the wavelength for each peak is determined with sub-picometer resolution and plotted in microstrain. This particular example involves 2 kHz switching between 4 wavelength bands resulting in a quasi-simultaneous observation of all sensors in all 4 bands at 500 samples per second..

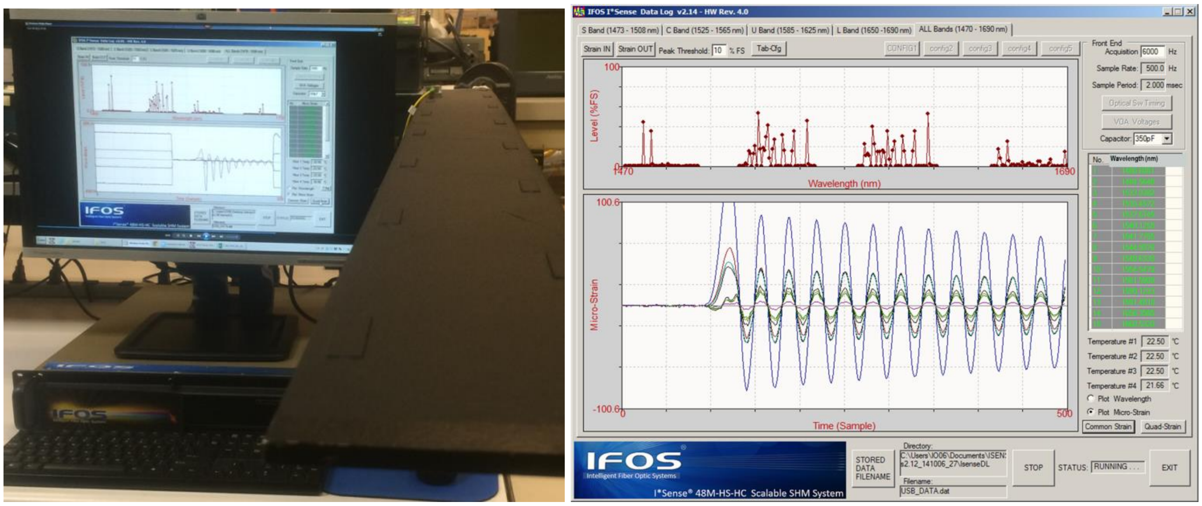

Figure 5. Monitoring of a cantilever beam with an interrogation unit capable of supporting 128 to 256 sensors together with example graphical user interface (GUI) based on dividing the wavelength spectrum into 4 groups of 48 channels from which the wavelength for each peak is determined to with sub-picometer resolution from which the strain is determined and plotted in microstrain.

Figure 6 provides two examples of dynamic measurements obtained using our baseline interrogation system designed for sampling at 6 kS/s (6 kilo-samples-per-second, providing a Nyquist frequency limit of 3 kHz). Figure 6(a) shows the dynamic strain measurement for 10 FBG sensors on a cantilever beam. Figure 6(b) provides an example test in a jet engine for a three sensor probe with sensor #3 being furthest into the engine and seeing both the hottest temperatures when the engine is running and coldest temperatures when it is shut down while the sensors #1 and #2 closer to the wall see a slower variation in temperature. For Figure 6(b), the system was running at 0.8 kS/s, which was sufficient to capture the on-off spikes in temperature seen especially by sensor #3.

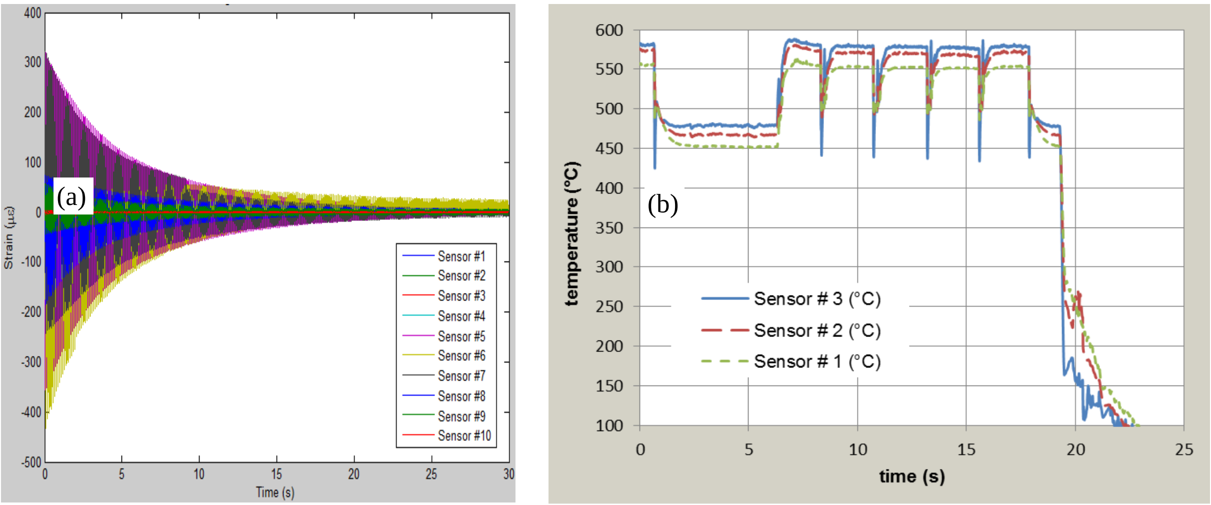

Figure 6. (a) Dynamic strain measurement at 6 kS/s (6 kilo-samples-per-second, providing a Nyquist frequency limit of 3 kHz) for 10 FBG sensors on a cantilever beam. (b) Dynamic temperature measurements for a 3-FBG sensor probe for measuring temperature profile inserted into a jet engine going with the power being periodically snapped from mid to fast-throttle, hold, and back, and finally turned off at t = 18.5 seconds.

5. HIGH FREQUENCY MEASUREMENTS

Composite Overwrapped Pressure Vessels (COPVs) are finding significant usage in the aerospace and transportation industries. Monitoring for proximity to failure is crucial for ensuring safe operation while maximizing useful life. AE monitoring is a reliable, non-intrusive system for the detection of damage in a COPV. The IFOS innovation involves (1) an ultra-high-speed (MHz), high resolution, small foot-print fiber Bragg grating (FBG) sensor interrogator, (2) signal processing algorithms to monitor AE signals in the presence of a quasi-static background strain field, and (3) new methods for integrating FBGs with COPVs. An example COPV provided by NASA and monitored at 3 mega-samples-per-second (MS/s) is shown in Figure 7. Example measurement results are shown in shown Figure 8 through Figure 10.

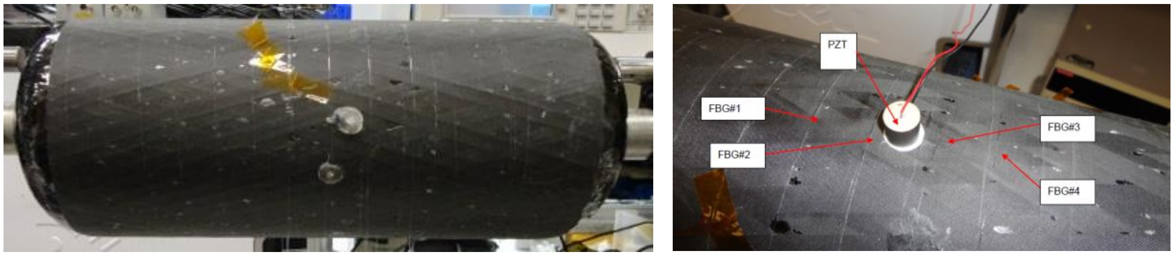

Figure 7. Composite Overwrapped Pressure Vessel (COPV) with 4 FBGs attached for monitoring by 3 MS/s system.

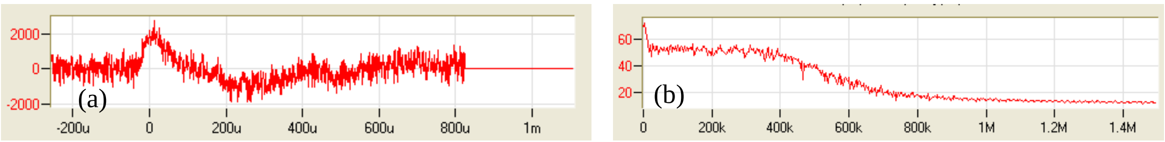

Figure 8. Example FBG readout for a pencil break test on a COPV interrogated at 3 MS/s allowing frequency providing a Nyquist limit for frequency readout of 1.5 MHz: (a) Time domain response: mV versus time in microseconds (u) to 1 millisecond (m). (b) Frequency domain response: Power (dB) versus frequency in kHz (k) to 1.5 MHz (M).

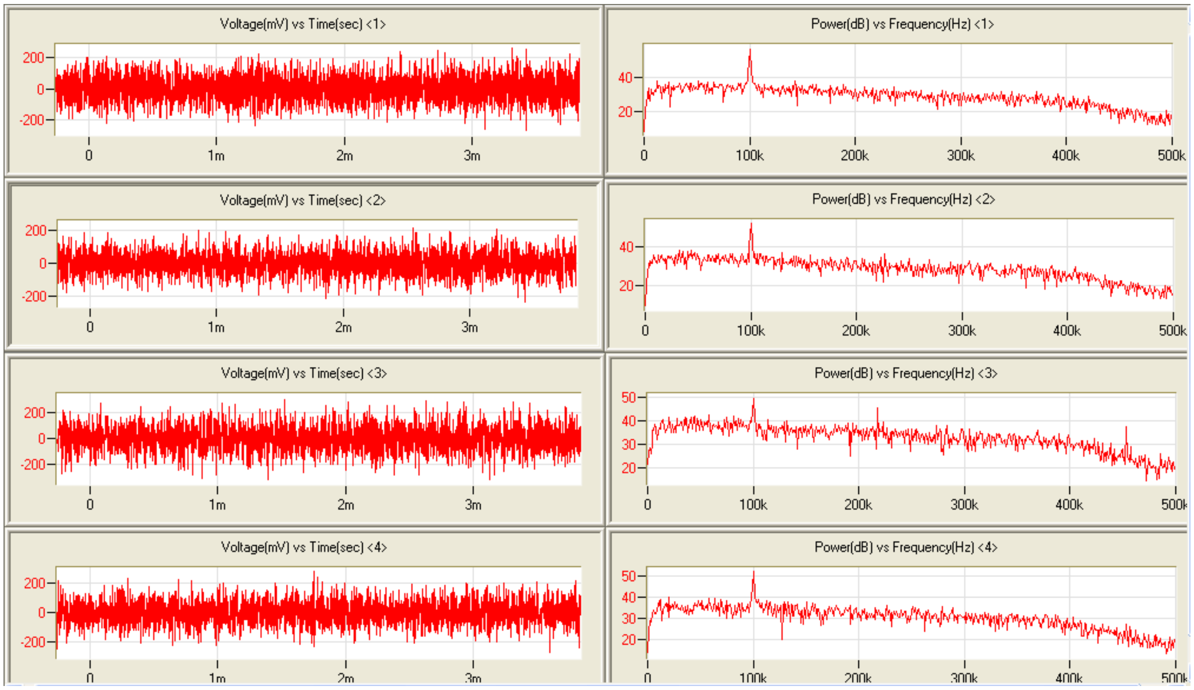

Figure 9. Example readout for 4 FBG sensors simultaneously sampled at 3 MS/s for COPV excited at 100 kHz with a PZT actuator. The frequency response is plotted to 500 kHz on the right.

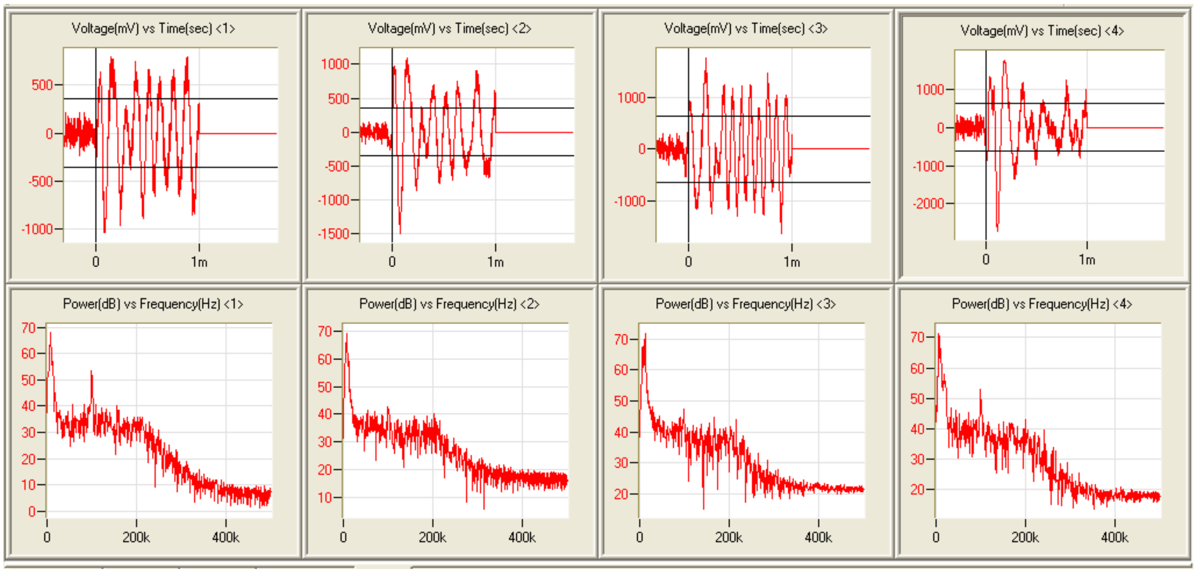

Figure 10. Example readout for 4 FBG sensors simultaneously sampled at 3 MS/s for COPV and gently “pinged” for 1 millisecond. The frequency response is plotted to 500 kHz on the right.

6. CONCLUSIONS

Electromagnetic-interference (EMI) immune, electrically passive and chemically inert, optical fibers are flexible, small-in-diameter, light-in-weight, embeddable into different materials and can be far-in-reach (kilometers in length). They enable distributed-sensing in harsh environments requiring temperature and radiation tolerance. With appropriate processing and packaging, they can be very robust and well suited to operational demands. In particular, FBG sensor arrays can provide multipoint, multifunctional sensing given an appropriate enabling FBG interrogation system. In this paper, we reviewed developments in fast FBG sensor interrogation system with scalability to support monitoring of large structures in harsh environments, and discussed operation over a large range of frequencies from quasi-DC to megahertz. This work is providing a path to a complete harsh-environment-tolerant end-to-end fiber optic sensor system that comprises (a) ruggedized sensor interrogators, (b) scalable packaged sensors and mechanisms (over one thousand), and (c) intelligent algorithms implemented in firmware or software for decision support.

7. ACKNOWLEDGMENTS

We thank Dr. Ignacio Perez, ONR Program Officer for Navy SBIR Phase II Contract N00014-11-C-0437, and his colleagues for insightful comments and support. Some of this work also benefitted from NASA support.

8. REFERENCES

[1] Hill, K. O. and Meltz, G., “Fiber Bragg Grating Technology Fundamentals and Overview,” J. Lightwave Technol., 15(8), (1997).

[2] Black, R. J., Zare, D., Oblea, L., Park, Y.-L., Moslehi, B. and Neslen, C., “On the gage factor for optical fiber grating strain gages,” SAMPE'08, 18-22 (2008).

[3] Black, R. J. and Moslehi, B., "Advanced end-to-end fiber optic sensing systems for demanding environments (Invited Paper)," Proc. SPIE 7817. 0L.1-9 (2010).

[4] Black, R. J., Costa, J. M., Moslehi, B., Zarnescu, L., Hackney, D. and Peters, K., "Fiber optic temperature profiling for thermal protection heat shields," Proc. SPIE 9062. Paper 41 (2014).

[5] Moslehi, B. and Costa, J. M., “Fiber optic pressure sensor based on differential signaling,” US Patent 8,402,834, (2013).

[6] Moslehi, B., Sotoudeh, V., Faridian, F., Costa, J. M., Black, R. J., A.Behbahani, O’Brien, W., Ha, D. S. and Austin, M., "Intelligent and Robust Sensors using Fiber-optic Network Distributed Engine Control," Proc. 57th International Instrumentation Symposium. 488 (2011).

[7] Moslehi, B., Black, R. J. and Faridian, F., [Multifunctional Fiber Bragg Grating Sensing System for Load Monitoring of Composite Wings, Paper 1557], Big Sky, MT(2011).

[8] Black, R. J., Chau, K., Chen, G., Moslehi, B., Oblea, L. and Sourichanh, K., "Optical fiber gratings for structural health monitoring in high-temperature environments," Proc. SPIE Sensor Systems and Networks - Phenomena Technology and Applications for NDE and Health Monitoring. 6530, 653001P (2007).

[9] Chan, T. H. T., Yua, L., Tam, H. Y., Ni., Y. Q., Liu, S. Y., Chung, W. H. and Cheng, L. K., “Fiber Bragg grating sensors for structural health monitoring of Tsing Ma bridge: Background and experimental observation,” Engineering Structures, 28, 648–659 (2006).

[10] Chang, F.-K., [Structural Health Monitoring 2009 – Proc. 7th International Workshop on Structural Health Monitoring] DEStech Publications, Lancaster, PA(2009).

[11] Tennyson, R. C., Mufti, A. A., Rizkalla, S., Tadros, G. and Benmokrane, B., “Structural health monitoring of innovative bridges in Canada with fiber optic sensors,” Smart Mater. Struct., 10, 560–573 (2001).

[12] Todd, M. D., Johnson, G. A. and Vohra, S. T., “Deployment of a fiber Bragg grating-based measurement system in a structural health monitoring application,,” Smart Mater. Struct., 10, 534–539 (2001).

[13] Black, R. J., Moslehi, B., Oblea, L., Yankelevich, D., Zare, D., Sathish, S., Schehl, N., Jata, K. and Neslen, C., "Fiber Bragg Gratings for Crack Growth and Thermal Monitoring," Proc. SAMPE '08. Paper L084 (2008).

[14] Park, Y.-L., Ryu, S. C., Black, R. J., Chau, K., Moslehi, B. and Cutkosky, M. R., “Exoskeletal Force Sensing End-Effectors with Embedded Optical Fiber Bragg Grating Sensors,” IEEE Trans. Robotics, 25(6), 1319-31 (2009).

[15] Moslehi, B., Black, R. J., Costa, J. M., Faridian, F. and Talnagi, J., [On-Line Monitoring of Flow-Accelerated Corrosion for Nuclear Power Plants] U.S. Department of Energy, (2011).

[16] Sotoudeh, V., Moslehi, B., Black, R. J., Oblea, L., Chen, G. and Randles, P. W., "Fiber Bragg Grating Arrays for Impact Damage Monitoring in Concrete," Proc. CONSEC'10 - Sixth International Conference on Concrete under Severe Conditions – Performance under Severe Loading (2010).

[17] Park, Y. L., Black, R. J., Moslehi, B., Cutkosky, M., Elayaperumal, S., Daniel, B., Yeung, A. and Sotoudeh, V., [Steerable Shape Sensing Biopsy Needle and Catheter - U.S. Patent Application filed Sept. 18, 2009 and assigned PTO serial number 12/562,855; Provisional Patent Application 61/175,399 filed May 4, 2009], (2009).

[18] Park, Y.-L., Elayaperumal, S., Daniel, B., Ryu, S. C., Shin, M., Savall, J., Black, R. J., Moslehi, B. and Cutkosky, M. R., "Real-Time Estimation of Three-Dimensional Needle Shape and Deflection for MRI-Guided Interventions," IEEE/ASME Trans. Mechatronics - Focused Section on Surgical and Interventional Medical Devices 15(6), (2010).

[19] Overton, G., [Photonics Applied: Optical Sensing: Downhole sensing puts fiber optics to the test], April 1, 2011 (2011).

[20] Kaura, J. and Sierra, J., "High-temperature fibers provide continuous DTS data in a harsh SAGD environment," World Oil(June), (2008).

[21] Wright, P. J., [The Future of Fiber Optics in the Offshore Oil Industry - http://www.odi.com/ODI_Documents/Articles_and_Papers/word_doc/Future%20of%20Fiber%20Optics.doc.].

[22] Yamate, T., "Fiber optic sensors for the exploration of oil and gas," 19th International Conference on Optical Fibre Sensors – Perth – Australia – Proc. SPIE, 7004, (2008).

[23] Normann, R., Weiss, J. and Krumhansl, J., [Development of fiber optical cables for permanent geothermal wellbore deployment], Stanford University, Stanford, CA(2001).

[24] Moslehi, B. and Black, R. J., "Knowledge Generation Employing Multi-functional Photonically Sensorized Environments (Plenary Talk)", International Conference on Applied Photonics Technology (IAPTC). (2011).

[25] Lopatin, C. M., Mahmood, S., Mendoza, E., Moslehi, B., Black, R., Chau, K. and Oblea, L., "Progress in miniaturization of a multichannel optical fiber Bragg grating sensor interrogator," Proc. SPIE 6619, Third European Workshop on Optical Fibre Sensors. 66193X (2007).