High-speed System for FBG-based Measurements of Vibration and Sound

Devrez M. Karabacak[*,a] , Selwan K. Ibrahim, Yorick Koumans[b], Bastiaan Meulblok [b], Rik Knoppers[b]
FAZ Technology Ltd, 9c Beckett Way Park West Business Park, Dublin 12, Ireland

ABSTRACT

Fiber Bragg Gratings (FBGs) allow for optical detection of localized physical effects without the need to couple the light out and back into a fiber, enabling robust and multiplexed sensor systems. The need of combining wide bandwidth and high resolution for dynamic sensing applications, like acoustics and vibrations, has presented significant challenges for FBG-based solutions. Here, we present a novel FBG-based measurement system enabled by using high-speed and high-precision tunable laser-based optical interrogation scheme. Multiple levels of integrated wavelength referencing coupled with low-noise high-speed electronics allow for spectral feature tracking at a resolution of <20 fm at kHz-frequencies. In combination with fiber accelerometers that employ unique force transmission mechanisms, amplifying strain on the Bragg grating and increasing the resonance frequency of the transducer, resolutions <10 µg (150 Hz bandwidth) to sub-mg resolution in kHz-frequencies is achieved. Similarly, compact wavelength-multiplexed hydrophones with wide range linearity and dynamic range, sub-Pa resolution and flat-sensitivity down to static pressures are demonstrated. The sensors are demonstrated to be customizable to application-specific requirements, and designed to be scalable to large quantity reproducible manufacturing.

In contrast to interferometry-based solutions, the tunable swept-laser detection scheme in combination with strain-based FBG sensors provides a cost-effective system that allows for easy scaling of sensor counts per fiber with multiple fibers being simultaneously recorded. Finally, the integrated high accuracy triggering and hybrid measurement capabilities present the potential to monitor sounds and vibrations in a wide range of applications from seismic surveys to machine and structural monitoring applications in harsh environments.

Keywords: Fiber optic sensors, Fiber Bragg Gratings, dynamic sensors, sensing systems, hydrophone, accelerometer

1. INTRODUCTION

Fiber Bragg Gratings (FBGs) are essentially wavelength-specific narrow band reflectors formed by refractive index variations in the core of the fiber. In their most simple form, the spacing of the periodic grating with respect to the effective wavelength of the light in the fiber core determines the wavelength of the reflection while the design of the grating along with its refractive index variation allows for adjustment of the reflectivity, the bandwidth and the spectral features of the reflected light [1]. Owing to their unique properties as such, FBGs have been successfully used in various applications, primarily in fiber optic communications field, in high precision reflectors for various multiplexing and de-multiplexing systems. Even in the early stages of using FBGs in passive filter applications, the strain sensitivity of the gratings was leveraged, whereby the strain-induced change in the spacing of the periodic grating that results in a shift of the reflection wavelength was used in manufacturing tunable reflectors [2,3]. Similarly, the FBGs also have well defined thermal response characteristics, resulting from a combination of thermally-induced refractive index change as well as the well-defined thermal expansion of the glass fiber resulting in change in the periodic spacing of the gratings.

In recent years, the above mentioned responsivities of the Fiber Bragg Gratings allowed for passive (electricity-free) strain and temperature gauges to be applied in various fields. The combination of the inherent advantages of fiber optics in low-loss long distance transmission and wavelength-specific localized sensitivity of Fiber Bragg Gratings provided some unique sensing system architectures: chains of passive sensors, wavelength multiplexed on low number of cost-effective optical fibers, distributed over large distances being recorded remotely and centrally, essentially forming quasi-distributed sensing systems.

---

*d.karabacak@fugro.com, telephone:+31-70-317-0588, fax:+31-70-11890
[a] Permanent affiliation: Fugro Technology BV, the Netherlands
[b] Permanent affiliation: Promolding BV, the Netherlands

Fiber Optic Sensors and Applications XIII, edited by Eric Udd, Gary Pickrell, Henry H. Du, Proc. of SPIE
Vol. 9852, 98520I · © 2016 SPIE · CCC code: 0277-786X/16/$18 · doi: 10.1117/12.2223005

In fact, one of the fundamental advantages of FBG-based sensing is reliant on the fact that various types of sensors can be mixed in a chain without the need for new interrogation hardware. This however requires the development of transducers that reliably generate sufficiently strong changes in the reflected optical spectra in response to external effects of various types.

There has, however been, relatively few applications of FBG-based dynamic sensors that operate at data acquisition bandwidths and resolutions comparable to electronic sensors, despite the inherent advantages of fiber optics for high frequency data transmission without cross-talk and noise pick-up, and the ability of lasers to record miniscule effects.

1.1 Challenges in Dynamic Sensing using Fiber Bragg Gratings

Three main parameters emerge for most dynamic sensing applications: resolution, dynamic range and frequency range. It is the primary goal of most sensors to be able to resolve the smallest change possible (resolution) without distortion in the measurement range required by the application (dynamic range) at largest range of speeds of change (frequency range). Clearly, there exists strong trade-offs between these parameters that need to be tackled from both the recording system and the sensor. To achieve the needed high resolution in dynamic sensors, it is highly desirable to combine the lowest noise interrogators that can track the reflection peak of the Fiber Bragg Grating with sensors that generate the highest possible wavelength shift with the smallest changes in the measurand, i.e. highest sensitivity. Here, the sensitivity of a Fiber Bragg Grating sensor is defined as the shift of the Bragg wavelength, where the peak reflectivity is achieved, per unit change in the measured parameter.

A limitation on the sensitivity is existent in most situations due to the operation range (dynamic range) needed from the sensor. In most transducers with mechanical components, the upper limit of sensitivity is introduced by the material properties. Here, glass fibers with their highly linear material characteristics provide an ideal platform whereby the upper limit of the sensitivity can be set close to the break strength of the grating, provided the transducer mechanism is suitably designed to not be the limiting factor. In most cases, Fiber Bragg Gratings with strengths reaching several percent strain can be obtained, especially using manufacturing techniques that avoid stripping and recoating of fibers [4,5]. Furthermore, the high stiffness to mass ratio of optical fibers fundamentally allow for very high modal frequencies to be achieved with Fiber Bragg Gratings. As such, wide bandwidth sensors can be realized with suitably designed transducers. However, the robustness and rigidity of optical fibers introduce challenges in ensuring sufficient changes of the grating length can be achieved to reach desired limit of detection. Such challenges can be overcome with design of transduction mechanisms that provide sufficient force and linearity. Furthermore, to retain the inherent advantages of fiber optic sensing, particularly robustness, low loss transmission and chain formation capability, it is highly desirable to have optical transmission through the sensor and the fiber as part of the transducer to avoid the need to couple the light out and back into the fiber. Here, Fiber Bragg Gratings form an ideal sensing element, owing to their localized and narrowband reflectivity that can be made susceptible to external forces while maintaining the light within the fiber and transmitting the remaining optical spectra through.

In this paper, we demonstrate two complimentary paths of recent developments that tackle the above described challenges while maintaining the inherent advantages of fiber optic sensing: high-speed high-resolution recording of Fiber Bragg Gratings using tunable laser technology and novel transducer designs that allow for high sensitivity over broad frequency range specifically for detection of pressure, sound, vibration and tilt.

2. HIGH-SPEED & ACCURACY INTERROGATION

To develop high precision and high speed FBG based optical sensing systems, the sensor needs to be designed to have a high bandwidth (BW) response and has to be interrogated with a high precision, high speed interrogator with a sampling frequency at least twice the maximum sensor signal frequency as well-known from Nyquist frequency theory. At the same time the interrogator should be able to interrogate multiple FBGs connected in series and multiplexed in the wavelength domain. This can be achieved by using a high-speed tunable laser based read-out system, referred to as the FAZT system. The FAZT optical interrogator is based on a semiconductor tunable laser diode that has no moving parts delivering high level of reliability and accuracy in addition to a power and wavelength reference section that includes several fine and coarse periodic wavelength references (e.g. etalon) [6]. The main basic building blocks of the interrogator is shown in Figure 1 below consisting of the transmitter section, polarization controller/scrambler, passive optics section which interfaces between the fiber sensor array and the receiver section, all connected and controlled by a computer on board (COB) which transfers the data to the end user/client via a high speed data communication link. The

FAZT system has been developed for both lab environments with high modularity, higher performance and integrated computation capability named as V4, as well as for in more compact form factor for field operations, as I4, as shown in Figure 1. The V4 interrogator is a 4U sized system based on the OpenVPX-VITA 46 standard with a programmable scan rate operating at 1, 10 or 44 kHz at 40, 4 and 1 nm scan bands, respectively, to provide tracking of optical spectra features such as the Bragg wavelength of gratings where the reflections peak. Also the system is capable of providing full spectrum data measurements of 40 nm with 1 or 5 pm sample sizes, at 200 and 1000 Hz data rates, respectively. The I4 interrogator (1U 19" sized rack system) as shown in (figure 1 (top-right)) can be used as a cost effective deployable system offering high speed interrogation of FBGs. The I4 is typically used for applications where the high spectral data capture offered in the V4 is not required.

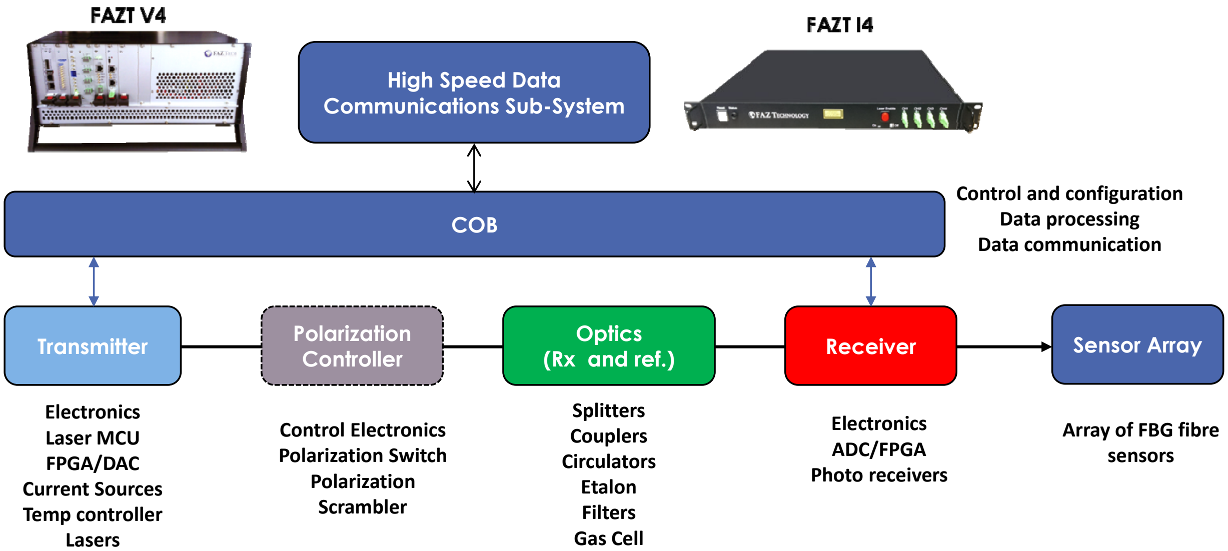

Figure 1. Block diagram of the FAZT tunable laser interrogator platform, demonstrating the modules of operation needed for a fully integrated interrogation of FBG-based sensors.

During the data acquisition, the wavelength output of the solid-state laser in both the V4/I4 interrogator is adjusted to sweep the 1528-1568 nm (standard telecom C-band) at a tuning rate of 0.1 pm/ns. The optical output of the laser is split over four separate fiber channels with equal power output (typically +3dBm/channel), with some of the optical power being tapped for referencing and calibration. The light transmitted to and reflected from the FBG sensors is received from the same fiber ports and routed to photodetectors in the system with a minimum detectable power (noise floor) at the receive end <-40 dBm. The received reflection signal optical spectra is sampled with 1 pm wavelength resolution and the four separate fiber optic channels can be configured to each simultaneously track up to 30 FBG sensors at the 1 kHz sample rate, totaling a potential 120 sensors being monitored at kHz-rates from one laser system. This high-data rate performance in sensor tracking is achieved by implementing the FBG peak processing algorithms in hardware on a field programmable gate array (FPGA) connected internally to a computer on board (COB) unit. The systems enable the streaming data over an ethernet connection with 0.1 Gbit/s and 1 Gbit/s for the I4 and V4 respectively.

The highly repeatable tunable laser combined with precise wavelength referencing enables long-term high precision measurements of spectral features under standard conditions down to measurement reproducibility of ~30 fm (1σ) over days demonstrated with NIST-calibrated HCN Gas Cell lines P10 (1549.7305 nm) as shown in Figure 2(a) [7, 8]. Furthermore, the long term absolute accuracy, defined as deviation from the certified value of the HCN gas cell, is demonstrated to be < 0.5pm, with a specification of being within 1 pm across the operation temperatures (0-55°C) and wavelength range (C-band), throughout the interrogator lifetime. Similar performance is also demonstrated using Fiber Bragg Gratings, as shown in Figure 2(b). For dynamic measurements, a repeatability of <25 fm (1σ) has been demonstrated within a sample rate is achieved for the V4 with 4.3fm (<5fm) for the filtered (@80Hz BW) de-trended data [8]. This reflects the minimum detected wavelength shift of a FBG peak which represents a low noise floor in the frequency domain.

Finally, it is important to highlight that especially for long term (static) measurements of FBG sensors, the above discussed polarization effects need to be carefully mitigated to isolate the measurements from polarization fluctuations that occur in the transmission fiber path from the interrogator to the sensor and back. Such effects can occur in standard fibers due to fiber movement, bending, and temperature, resulting in errors in FBG reflection peak determination due to polarization dependent frequency shift (PDFS) that occur in all FBGs, albeit at different magnitudes based on their production technique and grating design. While PDFS induced errors in FBG measurements, ranging sub-pm to 40 pm amplitude, has been overlooked in previous systems as being part of the noise, the new generation interrogation platforms such as that described here enable such high resolutions that polarization induced effects can become dominant noise factors. To overcome this limitation, a polarization switch or scrambler module is integrated in the system presented above, connected between the laser output and the FBG channels for polarization control providing the option to interrogate and mitigate polarization effects for different types of sensors using a 2-state polarization switch. For even higher resolution high-end applications, high speed scramblers and multi-state polarization switches can also be implemented in the same platform.

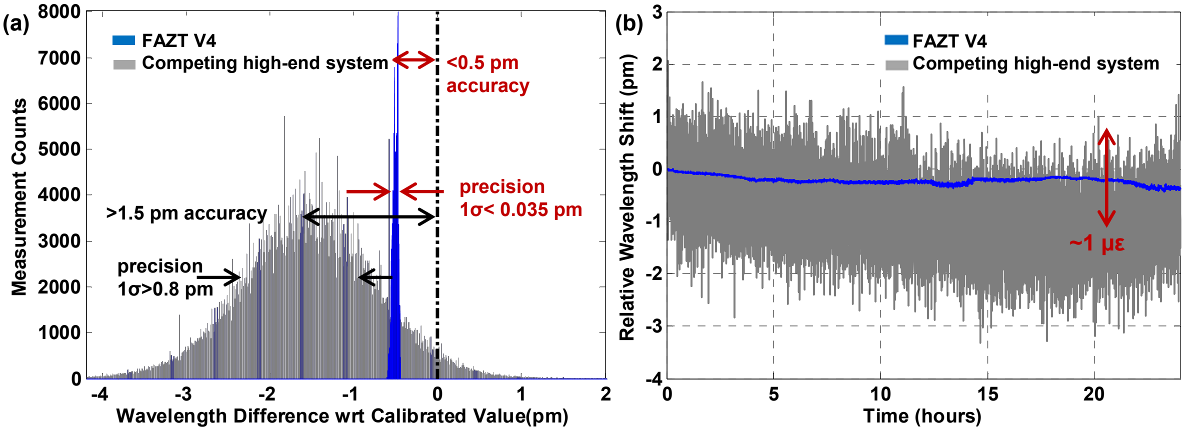

Figure 2.(a) Histogram of more than 61 hours of repetitive measurements (>430,000 readings) with the tunable laser system (FAZT V4) tracking a NIST-certified gas cell line (P10, 1549.7305 nm), demonstrating the repeatability of measurements to within 0.035 pm 1σ precision with < 0.5 pm offset. (b) Time trace of the same system performing differential measurement of two Fiber Bragg Gratings (with ~100 pm full width at half max reflection spectra and ~20% reflectivity) in uncontrolled environment over 24 hours with an accuracy of ~ 0.2 pm, corresponding to an effective strain of ~0.16 με on an FBG. For comparison data recorded from a competing high end system recorded with the same samples and under same conditions is provided.

3. MEASURING SOUND & PRESSURE

There exists many applications where fiber optic sensing of pressure, both static and dynamic, can provide significant advantages. In explosive or hazardous environments, such as pressurized tanks of hydrocarbon gases, fiber optics provide an inherently safe sensing scheme for, for instance, determining tank pressures and monitoring of safety during operations. In subsea, use of long chains of sensors without the need for electrical power and signal lines to record depth as well as acoustic signals can enable applications from localizing equipment and cables during operations to seismic surveys for geoscientific studies. In refineries and production facilities, a large distributed network of pressure gauges can be linked up without the need for expensive electrical power and data cables. Fiber Bragg Gratings have been proposed for pressure sensing for several such applications [9].

Traditionally, the pressure transduction schemes have relied on diaphragms or flexible membranes, whereby the fiber is attached either perpendicular to or on the surface of the flexible membrane such that deformation of the center of the diaphragm results in a stretching of the fiber [10,11,12]. There exists however, fundamental shortfalls in this approach whereby the membrane-based transduction element has significant limitations in the total amount of force and movement that can be generated in the optical fiber. To generate sufficient strain on the FBG over a large range, it is highly desirable to use a transducer element that itself has limited rigidity and has sufficiently large effective hydraulic diameter. However, membranes that have large effective areas also suffer strongly from nonlinear behavior unless they are very rigid. Furthermore, for the designs where the fiber is attached on the surface of the membrane, there exists considerable restrictions in the grating length, to 1-2 mm maximum, to ensure uniform strain across the grating for avoiding distortions on the spectral response of the FBG [11].

The above challenges can be overcome by the use of a novel transduction scheme based on bellows, pressure-sealed deformable bodies with large linear operation range. Such corrugated elements can be manufactured reproducibly in various effective hydraulic diameters and with different rigidities and linear displacement ranges. Figure 3 displays a pressure sensor based on bellow configuration whereby the Fiber Bragg Grating is stretched in length in response to the compression of the pressure-sealed transducer elements attached at the ends. The response of an FBG-based pressure gauge is shown in Figure 3(b), where gauge pressures going up to 3 bar generate up to 15.3 nm linear wavelength shift which is equivalent to 1.3% strain on the FBG.

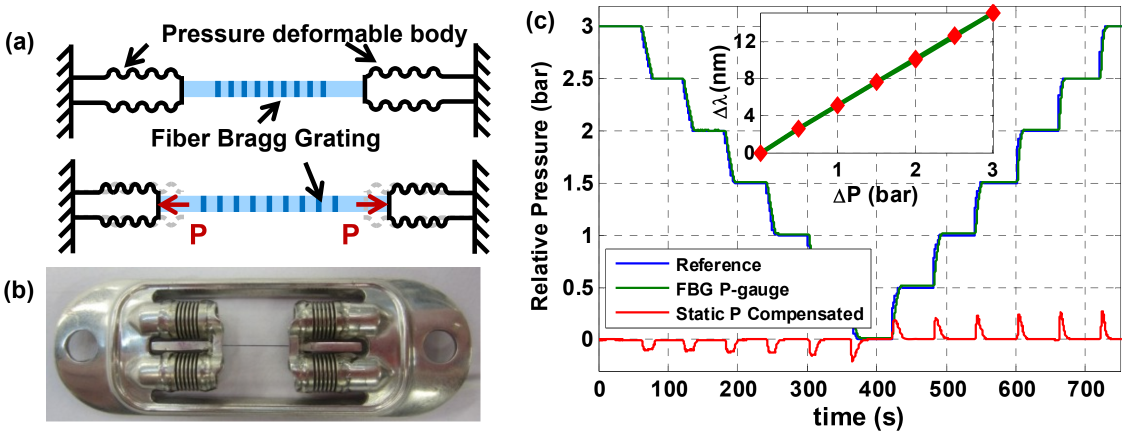

Figure 3.(a) A fiber optic pressure transducer whereby a fiber segment with a Fiber Bragg Grating (FBG) is stretched in response to increasing pressure that results in a compression of the transducers. (b) A picture of the FBG-based pressure transducer, and (c) the response of the same pressure gauge to steps of 0.5 bar pressure with a Bragg wavelength sensitivity of 5.1 pm/mbar. Inset shows the linearity of the response of the FBG-based pressure gauge across the measurement range even up to signals that reach 1.3% strain of the grating. The static pressure compensated hydrophone, with a similar dynamic sensitivity of 5.9 pm/mbar, returns to baseline within seconds of exposure to the static pressure.

The sensor described above allows for various sensitivities to be achieved by changing the effective hydraulic area of the transduction elements and the rigidity of the assembly. Furthermore, owing to the compact form factor and small effective mass of the assembly, very high fundamental modal frequencies are achieved, typically in the kHz-levels. As such, the transduction mechanism essentially forms an acoustic sensor that can operate with very flat response in frequency levels that are relevant for a range of applications, especially for subsea measurements and seismic recordings. Figure 4 displays a typical frequency response of three identically built FBG-based hydrophone according to the above described approach, demonstrating high flatness in amplitude and phase response with respect to a reference hydrophone, as well as the reproducibility among the prototypes. Here, it is important to emphasize that in contrast to alternative electrical approaches such as those based on piezoelectric transduction schemes, the fiber optic sensing mechanism depicts no loss of sensitivity at the lower frequencies and essentially forms a combined static and dynamic pressure gauge.

While the lack of low frequency cut-off of the FBG-based pressure sensor is beneficial in many applications for precise recording of static pressure levels, it can introduce challenges for certain applications where background pressure can hinder the resolution for recording the miniscule dynamic changes that are of interest. Furthermore, the presence of large background pressures can limit the dynamic operation range of the sensor due to limitations in the maximum allowable force on the Fiber Bragg Grating, often limited by the tensile strength of the grating, as addressed in previous section. Subsea acoustic scans that require the same sensitivity and dynamic range over large water depth range is one specific application where such challenges are clearly present. In such situations, a method of compensating the background pressure without lowering the higher frequency response, essentially forming a fully-mechanical high pass filter on the fiber, is highly desirable. Such an effect can be achieved in the FBG-based sensors described above by use of high viscosity fluid fillings that limit the motion of parts at high speeds, and thus forming parts that have frequency-dependent motion. In Figure 3(c), the response of such a static pressure compensated FBG-based hydrophone, with a recovery time of ~2 second, is plotted in comparison to an uncompensated hydrophone with a similar sensitivity. The observed response demonstrates the compensated sensor reacting for a brief period upon application of a pressure change with high frequency content (step-function) but as the speed of pressure change reduces, the system restores itself back to zero point. The response time scale has been demonstrated to be adjustable (not shown) to control the desired low frequency cut off point based on application needs.

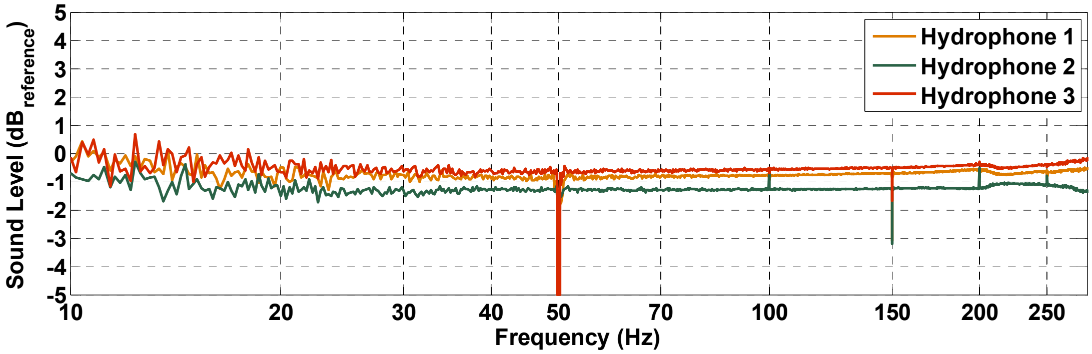

Figure 4. The frequency response of three FBG-based hydrophone with 40 fm/Pa sensitivities measured underwater at 4 meter depth, relative to a calibrated reference hydrophone (Bruel&Kjaer 8101), demonstrating high reproducibility and frequency flatness in response over a wide frequency range. The observed harmonics of 50 Hz is determined to be due to the electrical noise picked up by the reference hydrophone.

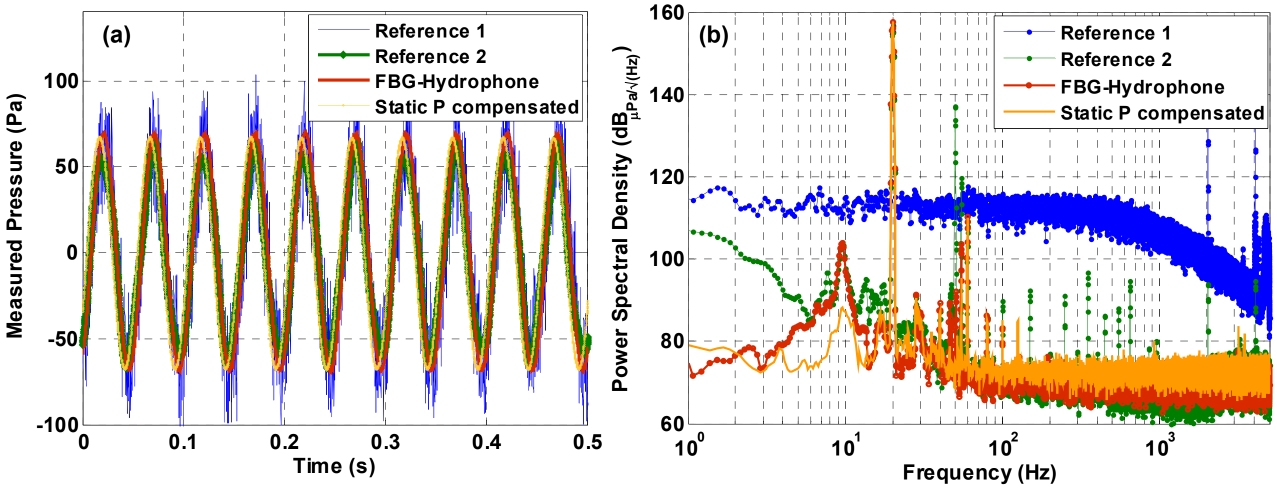

Figure 5. (a) Recording of a single tone sound at 20 Hz with an amplitude of 100 Pa_{rms} being recorded by both the uncompensated and static pressure compensated FBG-based hydrophones (from Figure 3) recorded at 10 kHz using the tunable laser interrogator described above, as well as a NIST-certified Omega MM-series pressure gauge (reference 1) and a Geospectrum M02 hydrophone (reference 2). (b) A power spectral density of the 20 Hz tone recording, demonstrating the very low noise and high dynamic range possible with the fiber optic interrogator system and the FBG hydrophones, across the frequency range from 1 to 5000 Hz. Strong interference of 50 Hz noise is observed in the electrical reference signals, missing in the optical measurements.

The dynamic response of the compensated, and the uncompensated, pressure gauges is further shown Figure 5 with an exposure to single tone of sound only 100 Pa_{rms} generating several orders of magnitude in signal to noise. Clearly, the dynamic response of the FBG-based hydrophone is not hindered by the static compensation scheme demonstrated above. Here, the combination of the FBG hydrophone with the high resolution interrogator described in previous section has resulted in a noise floor below 80 $dB_{\mu Pa/\sqrt{Hz}}$ up to 5 kHz. In an experiment performed in an acoustic resonance tube setup, sound levels generated up to 200 $dB_{\mu Pa}$ equivalent to seismic array gun shots down to sound levels equivalent to conversation sound levels of 80 $dB_{\mu Pa}$ can be recorded with one FBG-based hydrophone, as shown below in Figure 6. The achieved precision, noise level and dynamic range enable many high end applications, such as (subsea) seismic surveys, to be performed with a complete fiber optic system with arrays of wavelength multiplexed FBG hydrophones.

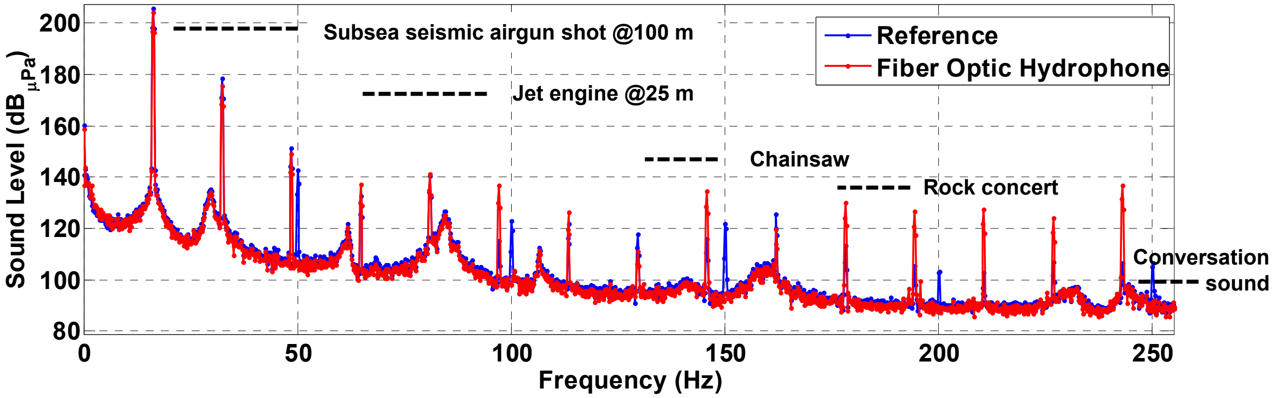

Figure 6. A swept frequency acoustic test result demonstrating the very wide dynamic range of the hydrophone, of Figure 5, in comparison to the reference (Geospectrum M02 hydrophone) where sounds as loud as seismic airgun shots and as low in amplitude as the conversation tones can be picked up by the same FBG-based sensor, measured with the laser system described in Section 2. The tones observed in the spectra are acoustic resonances of the test setup as confirmed by their simultaneous recording independently from both the electronic reference system and optical system. Several additional electronic interferences, in harmonics of 50 Hz, are visible in the electronic recording but not optically measured.

4. MEASURING VIBRATIONS AND ACCELERATIONS

Similar to the challenges of acoustic detection described in the preceding section, there exists a need for novel transducer designs for large-bandwidth high-sensitivity detection of vibrations and accelerations. Accelerometers in their most general form can be described as mass-spring mechanisms whereby the mass, often referred to as the inertial mass, is connected to a reference frame through a spring element such that inertial forces due to accelerations coupled into the frame result in a motion of the inertial mass with respect to the frame. Such relative motion, often very low in amplitude, can be very accurately measured by employing a Fiber Bragg Grating as (part of) the connection spring between the inertial mass and the reference frame.

In accelerometers, the correlation between acceleration and the motion of the mass will remain acceptably linear for low frequencies while the fundamental modal frequency of the formed mass-spring system will result in highly nonlinear behavior as the resonance frequency is approached and responsivity of the sensor to accelerations will degrade strongly beyond resonance frequency. As such, it is highly desirable to push the fundamental resonance frequency, defined to be proportional to $\sqrt{stiffness/mass}$, to as high a frequency as possible. However, increasing either the stiffness or lowering the mass both lead to decrease in the sensitivity of the system and as such is highly undesirable.

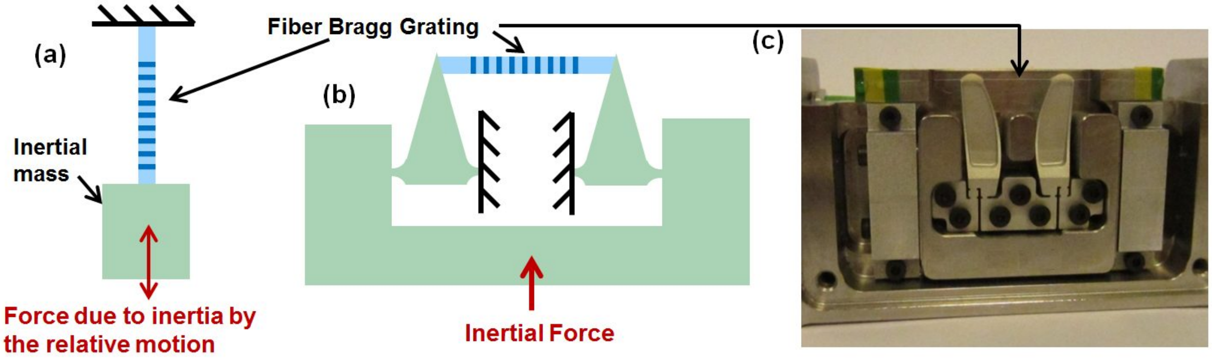

Figure 7.(a) The simplest accelerometer with the Fiber Bragg Grating forming the spring to detect inertia of the mass. (b) Schematic and (c) photograph of a novel force transmission system that enables enhanced sensitivity for a given frequency band of operation.

To enable design flexibility and enhanced performance within the above described constraints, an approach of transmission arm concept is presented here. The transmission system, shown in Figure 7 allows for the relative motion of the inertial mass to be coupled in an amplified manner to the Fiber Bragg Grating and as such amplifying the strain-based signal achievable. In Figure 8, a typical response of the FBG accelerometer to single tone frequency shaker signal is demonstrated with a signal at 0.2 pm/(m/s^2) at 100 Hz for an accelerometer with a Bragg wavelength sensitivity of 3.8 pm/(m/s^2).

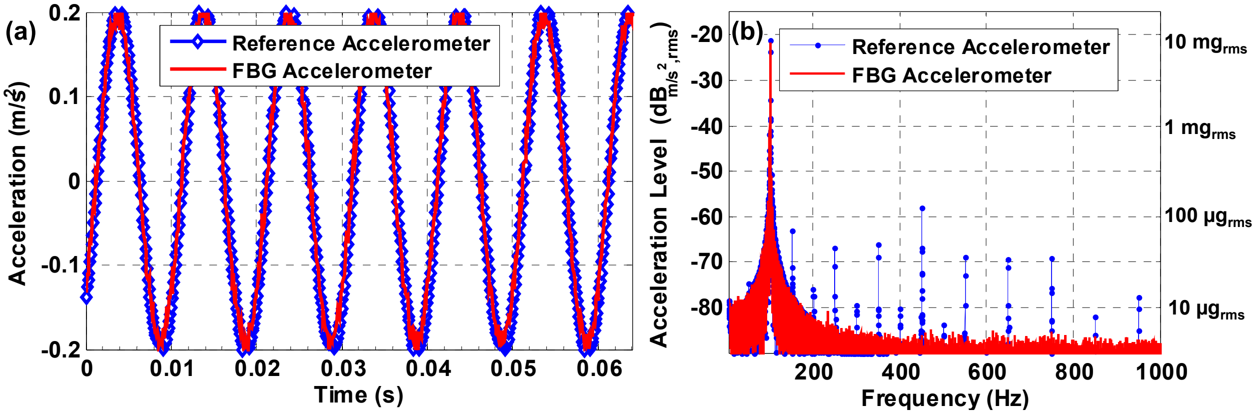

Figure 8. Time trace recording of a 3.8 pm/(m/s^2) sensitivity FBG-based accelerometer measured with a FAZ Technology V4 interrogator recording at 10 kHz in response to a vibration of 0.2 m/s^2 amplitude generated on a shaker table, in comparison to a certified electronic accelerometer (Bruel&Kjaer 4506B), and (b) the spectral plot of the response demonstrating the high signal to noise ratio of the sensor, even at relatively weak vibrations of approximately 0.1 m/s^2, with noise floors in the low-µg levels as shown. The peaks in the spectra of the reference accelerometer are determined to be electronic noise at harmonics of 50 Hz, not affecting the optical accelerometer.

By introduction of transmission ratio, a significant enhancement can be achieved in sensitivity for a given operation frequency band. Furthermore, the use of transmission arms allows for more compact form factor for a given frequency range accelerometer as well as a range of different accelerometers to be built on the same architecture. In Figure 9, four different accelerometers with sensitivities in the range of S_a = 0.5 – 110 pm/(m/s^2). Here, the trade-off is with the operation frequency range, whereby the achievable sensitivity S_a is quadratically proportional to the inverse of the resonance frequency; $S_a \sim 1/f_r^2$.

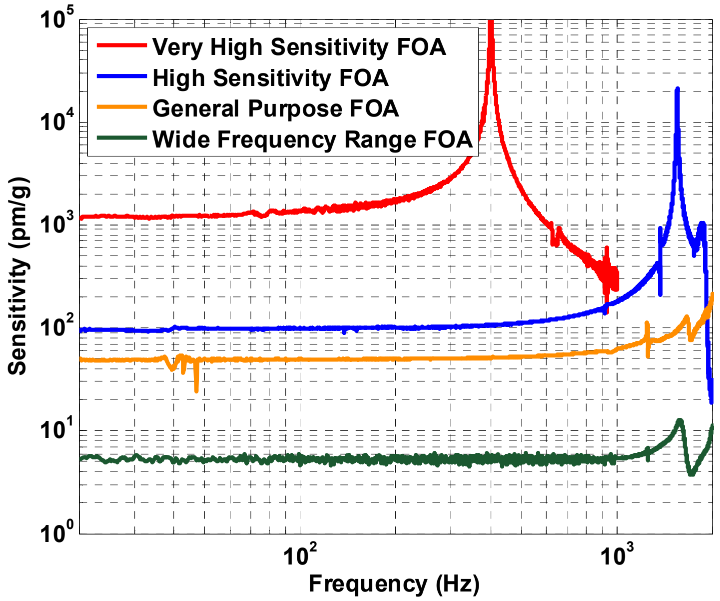

Figure 9. Spectral response curves of four FBG-based accelerometers with reflection wavelength sensitivities of 0.5 pm/(m/s^2) (wide frequency range), 5 pm/(m/s^2) (general purpose), 10 pm/(m/s^2) (high sensitivity) to 110 pm/(m/s^2) (very high sensitivity).

Finally, it is important to note that the fiber optic accelerometers, much like their counterpart acoustic sensors in the preceding section, have a constant sensitivity to 0 Hz, allowing for recording of static acceleration; earth’s gravity effect. By recording the magnitude of the effect of gravity on a single axis uniaxial sensitivity FBG accelerometer, the gravity direction and thus the tilt of the axis with respect to gravitational field can be determined. In Figure 10, this property is leverages whereby a tilt sensor is demonstrated by the measurement with an oscillatory rocking station operated at 6 second periodicity and +/- 15 degree amplitude, demonstrating a sensitivity of 21 pm/degree allowing for measurements of tilt with an accuracy up to 0.1 degree when coupled with the tunable laser interrogators described above. In a 3-axis combination, the same effect can be utilized for determining orientation of the unit and enabling precise determination of vibration directions with respect to gravitational field.

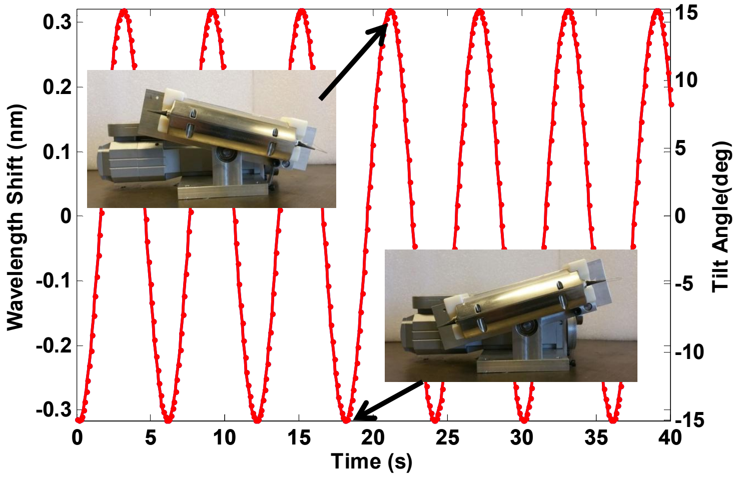

Figure 10. The response of a tilt sensor, built on the same concept of the very high sensitivity accelerometer plotted in Figure 9, demonstrating an FBG reflection wavelength sensitivity of 21 pm/degree and tilt measurement capability up to 1 degree accuracy and an operation range up to 200 Hz.

5. CONCLUSIONS

In the preceding sections, a high accuracy interrogation platform and an accompanying range of Fiber Bragg Grating technology based sensors have been demonstrated, beyond the well-established strain and temperature applications. An interrogation platform with fm-level resolution in tracking Bragg gratings at kHz-levels is described. With a novel set of transduction techniques, it is shown that standard optical fibers can be turned into sensors for pressure, sound, vibration, acceleration and tilt. The achieved performance of the hydrophones enable detection of Pa-level sounds even at large depths. When coupled with the tunable-laser based interrogation scheme, the FBG-based accelerometers are demonstrated to record vibrations with resolutions down to sub-μg levels and frequencies up to kHz. As such, they enable measurements for a wide range of applications from (broadband) machine monitoring to (high resolution) seismic surveys to tilt and orientation measurements.

The combination of the tunable laser based interrogation technique and the presented sensing solutions provide new opportunities for fiber optic detection systems that allow for both static and dynamic sensing of a wide range of parameters using sensors arrayed on a single fiber. By leveraging the wavelength multiplexing capability of Bragg gratings and the ability of the FAZ interrogation platform to record multiple fibers simultaneously, both the cabling and the signal acquisition and digitization costs can be shared across many sensors resulting in very cost competitive multiparameter sensing systems.

REFERENCES

[1] Hill, K. O., and Meltz, G., “Fiber Bragg Grating Technology Fundamentals and Overview,” Journal of Lightwave Technology, Vol. 15, No. 8, 1263-1276 (1997).

[2] Mohammad, N., Szyszkowski, W., Zhang, W.J., Haddad, E.I., Zou, J., Jamroz, W. and Kruzelecky, R., “Analysis and development of a tunable fiber Bragg grating filter based on axial tension/compression,” Journal of Lightwave Technology, 22(8), 2001, (2004)

[3] Goh, C.S., Set, S.Y. and Kikuchi, K., “Widely tunable optical filters based on fiber Bragg gratings,” Photonics Technology Letters, IEEE, 14(9), 1306-1308 (2002)

[4] Rothhardt, M. W., Chojetzki, C., and Mueller, H. R., “High-mechanical-strength single-pulse draw tower gratings,” Proceedings of SPIE 5579, Photonics North 2004: Photonic Applications in Telecommunications, Sensors, Software, and Lasers, 127 (2004).

[5] Kang, D. H., Park, S. O., Hong, C. S., and Kim, C. G., “Mechanical Strength Characteristics of Fiber Bragg Gratings Considering Fabrication Process and Reflectivity,” Journal of Intelligent Material Systems and Structures, 18, 303-309 (2007).

[6] Ibrahim, S. K., O'Dowd, J., McCue, R., Honniball, A. and Farnan, M., “Design Challenges of a High Speed Tunable Laser Interrogator for Future Spacecraft Health Monitoring,” CLEO: Applications and Technology, ATu1M-3, (2015).

[7] Gilbert, S. L., Swann, W. C. and Wang, C. M., “Hydrogen cyanide H13C14N absorption reference for 1530 nm to 1565 nm wavelength calibration–SRM 2519a,” NIST special publication, 260, p.137, (2005).

[8] Ibrahim, S. K., Farnan, M., Karabacak, D. M., Singer, J. M., “Enabling Technologies for Fiber Optic Sensing,” Proceedings of SPIE Photonics Europe, *accepted* (2016).

[9] Spirin, V. V., Shlyagin, M. G., and Miridonov, S. V., “Fiber Bragg grating sensor for petroleum hydrocarbon leak detection,” Optics and Lasers in Engineering, 32, 497-503 (1999).

[10] Sheng, H. J., Liu, W. F., Lin, K. R., Bor, S. S., and Fu, M. Y., “High-sensitivity temperature-independent differential pressure sensor using fiber Bragg gratings,” Optics Express, 16, 16013-16018 (2008).

[11] Urban, F., Kadlec, J., Vlach, R., & Kuchta, R., “Design of a pressure sensor based on optical fiber Bragg grating lateral deformation,” Sensors, 10, 11212-11225 (2010).

[12] Huang, J., Zhou, Z., Wen, X., and Zhang, D., “A diaphragm-type fiber Bragg grating pressure sensor with temperature compensation,” Measurement, 32, 1041-1046 (2013).