# Design Challenges of a High Speed Tunable Laser Interrogator for Future Spacecraft Health Monitoring

**Selwan K. Ibrahim, John A. O'Dowd, Raymond McCue, Arthur Honniball, Martin Farnan**
*FAZ Technology Limited, 9C Beckett Way, Park West Business Park, Dublin 12, Ireland*
*selwan.ibrahim@faztechnology.com*

**Abstract:** We report the performance results achieved for a high speed, high resolution optical FBG interrogator with a repeatability <5fm@80Hz BW and precision <200fm (p-p), designed for space applications on a launcher or atmospheric re-entry vehicle.

**OCIS codes:** (120.4800) Optical standards and testing; (060.2370) Fiber optics sensors

## 1. Introduction

There has been an increased interest in the recent years to use fiber optic sensing for space applications such as installing optical sensors on satellites, launchers (i.e. Ariane 5), atmospheric re-entry vehicles and solar sails in addition to ground testing of space structures [1]. Such applications include monitoring temperature, pressure, acceleration, and static/dynamic strain. Optical fiber sensors using Fiber Bragg Grating (FBG) technology fundamentally measures temperature (typically 10pm/°C) and strain (1.2 pm/$\mu\varepsilon$) [2]. Designing transducers around standard FBGs and/or writing FBGs on special fibers and in different configurations enables measurements beyond strain and temperature (e.g. pressure, acceleration, acoustics etc.). There are several advantages of using fiber optic sensing such as light-weight when compared to the current cable harnesses for electrical sensors, immunity to electromagnetic interferences, and the feature of multiplexing and distributing several sensors on a single fiber.

However, in addition to designing sensors, an optical FBG interrogator (reader) is required to measure the sensors with high level of accuracy, and at high acquisition speeds. It is also required to mitigate and reduce any errors induced from the sensors due to its sensitivity to unwanted physical effects such as polarization dependent frequency shift (PDFS). The interrogator should also operate in extreme conditions for certain space applications (e.g. launchers). In this paper we demonstrate a high speed, accuracy, and sensitivity optical FBG interrogator (FAZT V4) designed and tested under a European Space Agency (ESA) contract: "High speed tunable laser interrogator for spacecraft health monitoring". The interrogator also has in-built features to mitigate and overcome several effects such as vibration, temperature, aliasing, PDFS, and attenuation, while maintaining absolute sensor accuracy and high speed.

## 2. Interrogator Specifications

The FAZT V4 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). The key critical components of the system (Tunable Laser and Etalon) were tested and validated for use in a launcher environment by subjecting them to extreme temperature and vibration tests. The vibration tests included resonance tests up to 2.5g, sinusoidal tests up to 22.5g, and random vibration tests up to 20g all over 3-axis within a 5-2000Hz frequency range, while the thermal tests covered an operating range from -20°C to +70°C. The environmental tests proved that the components may be used before, during and after a launcher take-off. The V4 system is ruggedized and based on OpenVPX-VITA 46 standards. The laser in the V4 scans the C-band (40nm) at a rate of 1kHz (tuning rate of 0.1pm/ns) and the output power is split over four separate channels (typically +3dBm/channel) with the minimum detectable power at the receive end ~-45dBm. The received reflected signal is sampled with 1pm resolution and the V4 can capture and report full spectrum measurements (40nm@1pm sample size) at 250Hz rate. The four separate fiber optic channels can each simultaneously measure up to 31 FBG sensors @1kHz sample rate (124 sensors in total). This 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 which enables streaming data over a 1Gbit/s Ethernet connection. The highly repeatable tunable laser combined with precise wavelength referencing enables high resolution, low noise measurements for dynamic measurements (AC) (repeatability of <20fm (1$\sigma$) @1kHz sample rate) and long term high precision measurements (DC) (precision <200fm (p-p) or <30fm (1$\sigma$) measured by tracking HCN Gas Cell lines [3, 4]). The long term absolute accuracy (bias from the true value) over the V4 operating target temperature (0-55°C) and wavelength range (C-band) is <1pm. This may be improved to <0.25pm when operating at room temperature. Figure 1 (left) shows an example of a FBG (40pm FWHM) peak tracked @1kHz sample rate over 40 seconds. The slow drift was due to the FBG drift with temperature and the p-p noise was measured to be ~50fm. The probability density function of the normal distribution for the 40s data is shown in figure 1 (right). The repeatability (standard deviation) measurement of the de-trended (AC) un-filtered data (@500Hz BW) was measured to be 12.4fm, while the filtered (@80Hz BW) standard deviation was measured to be 4.3fm (<5fm). This reflects the minimum detected wavelength shift of a FBG peak which represents a low noise floor in the frequency domain. It is also used to define the dynamic range measurement for an acoustic frequency measurement (e.g. vibration tones and acoustic frequency measurements).

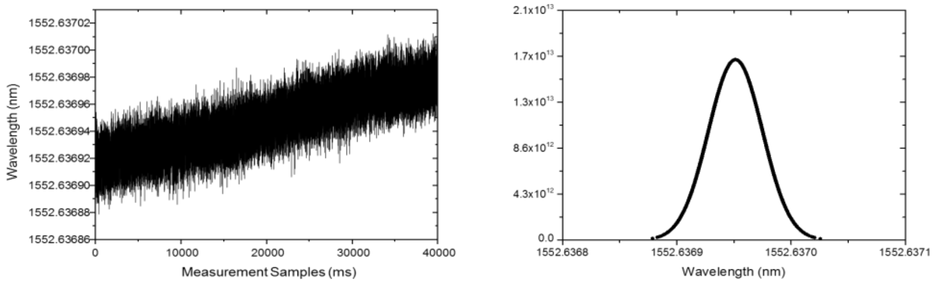

Fig. 1. FBG peaks tracked at 1kHz over 40 seconds (Left), probability density function of the peaks measured over the 40 seconds (Right).

The FAZ interrogator also includes the option to interrogate and mitigate polarization effects for different types of sensors using a 2 state polarization switch. There is also an option to support high speed scramblers and multi-state polarization switches which could be required for certain applications. PDFS in FBG sensors could be in the range of 1pm up to 40pm and higher depending on the type of FBG and birefringence induced due to the packaging.

## 3. Sensor Measurements

A test was carried out to validate the FAZT V4 interrogation of a FBG temperature sensor using a calibrated dry block, and a high precision thermometer. The FBG was first tested without any polarization mitigation technique. The results showed the FBG sensor deviating from the calibrated data by ±7pm equating to an absolute accuracy of ±0.7°C due to the PDFS induced calibration error in the sensor. To overcome this error, a polarization mitigation method using a 2 state polarization switch was used to measure a recalibrated sensor taking the PDFS into account. This reduced the error to < ±1pm, equating to an absolute accuracy of ±0.1°C measured over the full temperature cycle -20°C to +80°C as shown in figure 2 (left). This was within the desired results of ±5pm or ±0.5$^{o}$C for the ESA project requirements. Another test was carried out to measure the FBG response against a calibrated electrical strain gauge with the objective to demonstrate micro-strain measurements of ±1200με, using three electrical strain sensors, and two FBG strain sensors mounted on both sides of a calibrated cantilever system. Similarly, without using a polarization mitigation recalibrated system, the deviation from the electrical sensors was -2 με to +6 με for the concave, and 0 με to -20 με for the convex. However, with re-calibrating and mitigating the PDFS of the FBG strain sensor, the results showed a difference in accuracy of ±3με for the concave, and ±4με for the convex as shown in figure 2 (right) which is within the desired ±10με accuracy required for the ESA project.

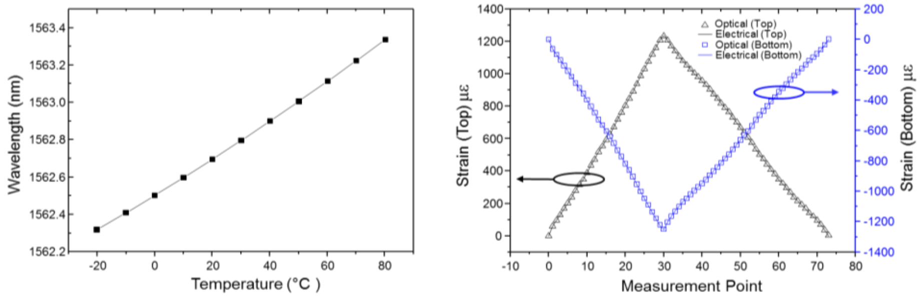

Fig. 2. Temperature measurements (Left), strain measurements for optical/electrical strain sensors mounted on both sides of a cantilever (Right).

## 4. Conclusion

We have demonstrated an optical interrogator with high resolution noise measurements by achieving repeatability values of <5fm using standard FBGs and long term precision measurements of <200fm (p-p) using NIST standard HCN gas cells. Using a polarization mitigation technique we demonstrated temperature measurements -20°C to +80°C with accuracies of ±0.1°C, and strain measurements of ±1200 με with accuracies of ±4 με. These measurements demonstrate that optical sensors and interrogators can be used for space applications.

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## 5. References

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