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PIC based FBG Interrogator Designed for High Accuracy and Low Noise Seismic and Dynamic Measurements

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Abstract: We propose and demonstrate using photonic integrated circuit (PIC) technology, a tunable-laser based FBG interrogator suitable for low noise seismic applications sampling at kHz rates and delivering <120dB re(nm^2/Hz) noise floor over a 500Hz bandwidth.

1. Introduction

Optical fiber sensing has been applied to several applications including civil engineering, marine, oil and gas, medical, energy, space, etc. [1, 2]. Optical sensing systems such as Fiber Bragg Grating (FBG) based optical interrogators have benefited from the recent developments in the fiber optic communication industry that resulted in the availability of high volume, low cost optical components that are used to develop optical interrogators (e.g. lasers, couplers, filters, photodiodes, etc.). Optical communication systems have been advancing photonic integration technology to achieve small footprint, high performance telecom systems. However, photonic integration can also be used in a wider range of applications beyond telecommunication, such as sensing, medical, Lidar, etc. Photonic integration is offered in different technology platforms (e.g. InP, Si, Silica, TriPlex, etc.), where each platform offers certain features and limitations (e.g. support of active elements, waveguide size, waveguide loss, etc.). FBG interrogators can benefit from photonic integration which offers scalability, improved performance, and small footprint [5]. In FBG based fiber sensing systems, the grating written in the fiber is the basic sensing element that inherently can measure strain and temperature (typical temperature sensitivity (~11pm/°C), strain sensitivity (~1.2 pm/με) @1550nm) [1,2]. An interrogator with <1pm absolute wavelength accuracy and <0.1pm wavelength precision specifications, when combined with FBG based optical sensors delivers an accuracy equivalent to (<0.1°C or <1με) and a precision (<0.01°C or <0.1με) which are desirable specifications for a wide range of sensing systems. To measure beyond strain and temperature, a transducer sensor must be designed to translate other physical effects (e.g. pressure, acceleration, etc. to strain on an FBG) [6]. The sensor is connected to the measuring device (optical interrogator) which detects the optical signal response and converts it to a measurement generating data which is then displayed or logged/stored for further processing and analytics.

Here we have developed and demonstrated a tunable laser based FBG interrogator using PIC technology combined with an InP electronically tuneable laser to deliver high-speed and high-performance measurements at kHz sweep-rates suitable for dynamic and seismic applications. We also demonstrate low noise seismic measurements by combining high performance FBG interrogators with high sensitivity FBG based accelerometers.

2. FBG Interrogator Design

As part of the EU PARADAIGM project, we participated in an InP multi-project wafer (MPW) run organized by JePPIX and designed a 4×6mm^2 InP chip that was manufactured by the Fraunhofer Heinrich Hertz Institute (HHI) foundry (Germany) and packaged by Tyndall National Institute (Ireland) in a 66.7×30mm^2 custom designed multi-fiber package [5]. The InP chip included several elements from the FBG interrogator optics including a 2GHz FSR Mach Zehnder Interferometer (MZI), optical splitters, and photo diodes. The performance of the interrogator using that PIC was demonstrated in [5] and achieved >120dB signal dynamic range. InP offers a range of passive and active building block components (i.e. Lasers, Amplifiers, etc.) which makes it attractive in terms of overall functionality. However, the waveguide propagation loss in InP PICs tend to be higher than what is achieved with other platforms (e.g. Silica based Planer Lightwave Circuit (PLC)) [3, 4]. Silica based PLC is a mature technology that has been used in the telecom industry over the last decades offering high volume, low cost, and low loss passive optical components (e.g. PLC 1×N splitters, AWG devices) [4]. A large section of the optical interrogator contains passive components based on fiber-based devices. These passive fiber components are assembled in an optical module requiring manual splicing, and assembly time which limits scalability for high volume, low cost solutions. Silica based PLC PICs allow cost effective production scalability, smaller footprint, and improved stability and performance [4]. Figure 1 shows a schematic of an FBG interrogator using a Silica PLC PIC device manufactured by Enablence which replaces most of the discrete passive components in the interrogator (e.g. splitters, circulators, MZIs, etc.).

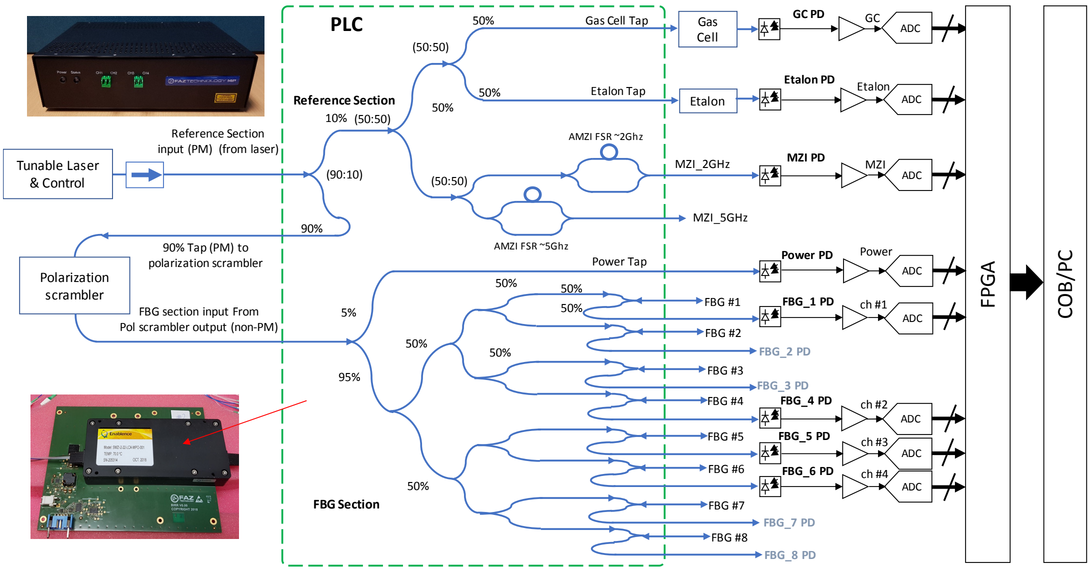

Fig. 1. Schematic diagram of the Silica PLC PIC based optical interrogator.

The Silica PLC PIC device also includes two MZI circuits (FSR of 2 and 5 GHz) and could support up to 8 FBG channels. The source in the tunable laser interrogator system is based on an electronically tuned telecom semiconductor InP based tunable laser (MG-Y) calibrated to deliver high repeatability and capability to scan the full C-band (~40nm) at 1kHz or 2 kHz speeds (equivalent tuning rate of 0.1 pm/ns or 0.2pm/ns). It can also sweep at higher rates over a narrow band (e.g. 4kHz@18nm or 8kHz@8nm) which is important for certain high frequency vibration or acceleration measurements [1,5]. The tunable laser output power is split to provide a signal for a wavelength reference section and a signal for the FBG channels via a polarization scrambler (e.g. Passive Lyot depolarizer) supporting four separate FBG channels out of the available 8 FBG channels using 3dB couplers as shown in figure 1. The interrogator incorporates several wavelength references, such as a Gas Cell (absolute wavelength reference), Athermal Etalon (coarse periodic wavelength reference), and MZI (fine periodic wavelength reference) to guarantee high accuracy and precision measurements over its target operating temperature range and life time. The wavelength references are used to correct any short- and long-term non-linearity, drift, and noise in the laser which enables the interrogator to deliver long term absolute accuracy of <±1pm (bias/deviation from NIST reference HCN gas cell) [2] and short-term repeatability/resolution of <20fm (standard deviation of FBG peak tracking over 10 seconds). In the current design the Gas Cell device is spliced externally to provide a long-term temperature independent absolute wavelength reference in the system. For dynamic and relative measurement applications it is possible to operate the interrogator without the Gas Cell. A future Silica PLC PIC design could use an AWG to replace the external athermal 25GHz FSR Etalon as the PLC chip temperature can be maintained at a fixed temperature. The FBG channels allow multiplexing of multiple FBG sensors (up to 30 FBG sensors) on a single fiber by using wavelength division multiplexing techniques. The receiver photodiode detects the reflected response from the FBGs and converts it to an electrical signal which is then sampled using analogue to digital converters (ADC) for further processing in the digital domain including a field programming gate array (FPGA) and a computer on board (COB). By implementing the peak processing algorithms in the FPGA, the interrogator can process 120 FBG peak sensors simultaneously at kHz rates in real-time. The data is then formatted and transferred over a data bus (e.g. Ethernet, USB, etc.) to a client for analysis, storage or feedback and control.

Understanding and minimizing the instrument noise is very important for most measurement systems and especially for seismic measurement systems. The main sources of noise for a typical seismic measurement system is dominated by the pink noise (1/f), Brownian noise ($1/f^2$) and high frequency white noise ($1/f^0$) [7] and can be quantified by measuring the power spectral density of the instrument output when no input is applied (terminating the inputs of an electronic measurement system or using a stable optical reference sensor for an optical measurement instrument) as shown in figure 2 (left). Having an instrument with a flat low noise floor covering frequencies from the sub Hz to the kHz range is very desirable for a lot of seismic and micro-seismic measurement applications. Also, if the instrument noise is mainly random having a uniform normal distribution (e.g. Gaussian), sampling the data at higher frequencies offers an improvement in the noise floor [7] (e.g. oversampling by a factor of n typically achieves a $\sqrt{n}$ improvement in noise performance). Sweeping the laser over a narrower wavelength range at higher speeds e.g. 18nm@4kHz and 8nm@8kHz allows an improvement in the average noise floor of the system (between 1Hz and 500Hz) as shown in figure 2 (middle) delivering >130dB dynamic range for an FBG sensor designed for a full-scale shift >1nm and sampled at 8kHz.

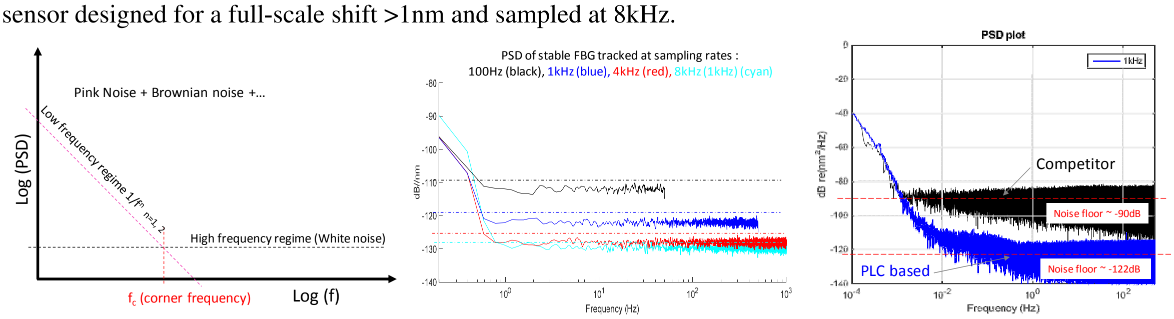

Fig. 2. Typical noise response of a seismic recorder as shown on a PSD plot (left), PSD plot of a stable FBG tracked with a FAZ interrogator at 100Hz, 1000Hz, 4000Hz, and 8000Hz (middle), PSD plot of an FBG tracked at 1 kHz over 3 days (PSD window size = 24 hours) for the Silica PLC PIC based interrogator (blue) and a competitor swept source based interrogator (black) (right).

To measure the noise floor of the system, an FBG sensor placed in a stable lab environment was tracked using the PLC based interrogator operating at 1 kHz sampling rate and measured over 3 days. The power spectral density (PSD) (relative to 1nm) plots for the tracked FBG sensor is shown in figure 2 (right) and is compared to a competitor swept laser interrogator tracking the same sensor at 1kHz. The PSD window used for the plot was equivalent to 24 hours so that the low frequency noise can be quantified with better resolution. The noise floor (between 1Hz and 500Hz) was measured to be~-122dB, while for a competitor swept source interrogator tracking the same FBG, it was measured to be ~-90dB. The FBG tracked wavelength peak varied by ~7pm (P2P) due to the influence of temperature change in the lab (FBG temp. sensitivity ~10pm/ºC @1550nm). This sensor drift and any residual drift in the instrument could explain the slight bump in the noise floor observed between 0.01Hz and 1Hz. In addition to tracking the FBG sensor, a trough of a 50 Torr HCN gas cell (GC) (P10 absorption line) was tracked at 1kHz. The gas cell offers a stable reference that can be used to measure the absolute accuracy and stability of the interrogator. The PSD in the low frequency range (0.1-1Hz) for the GC P10 absorption line was lower compared to the FBG measurement due to the high stability of the gas cell reference (~0.3pm P2P drift for the GC vs. ~7pm P2P drift for the FBG). The 50 Torr HCN gas cell was also used to measure the absolute accuracy of the PLC based interrogator, where 41 absorption lines across the C-band were detected using the interrogator and compared to a NIST standard datasheet [2] as shown in figure 3 (left) achieving <±1pm (P2P) absolute accuracy error over 0-55°C temperature operating range. The PLC packaged device had a built-in heater with a controller that maintained the chip temperature at 70°C which was selected to be higher than the interrogator max operating temperature @55°C. The time trace and histogram plots of the 50 Torr HCN gas cell line [P10 @1549.7302nm] tracked over 3 days @1 kHz sampling rate and down sampled to 2Hz is shown in figure 3 (middle) and (right), respectively using a Silica PLC PIC interrogator and compared to a commercial swept source competitor interrogator. The long-term precision (1σ standard deviation) of the tracked P10 trough measured over 12 hours using the PLC interrogator was ~27fm vs. ~823fm for the measurement using a commercial competitor 2Hz swept source interrogator.

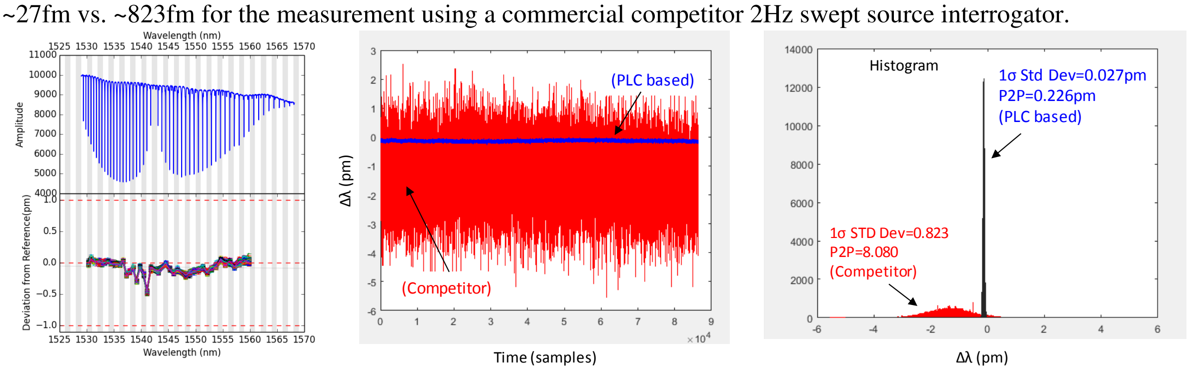

Fig. 3. Spectrum of a 50 Torr HCN gas cell and measured absolute accuracy of the interrogator for the corresponding gas cell line troughs (left), time trace (middle) and histogram (right) of a P10 gas line wavelength offset from the NIST specification measured over 12 hours and down sampled to 2Hz (blue) compared to a competitor swept source interrogator (red).

3. Fiber Sensing for Dynamic and Seismic Applications

FBG sensing solutions can be used for dynamic sensing applications where high sampling rate measurement systems (kHz sampling rates), high resolution (fm level noise floor for FBG peak tracking), and high dynamic range (>120dB max-min FBG peak variation) are required. These fiber sensing solutions can be applied to different fields and industries such as vibration based structural health monitoring in civil engineering, condition and structure monitoring in the Oil and Gas industry, etc.

Seismic sensing systems based on geophones, hydrophones, and accelerometers are important tools applied for different applications from Oil and Gas exploration to detecting earthquakes and other seismic events. Seismic studies for oil and gas exploration typically involves a seismic source to generate seismic waves at one or multiple locations. An array of seismic sensors is deployed to detect the seismic waves that travel into the earth and reflect back by the various geologic layers. The sensor array might contain hundreds of geophones for on-shore surveying, and hydrophones for off-shore surveying. The data from each sensor needs to be collected simultaneously with accurate timing, and then processed to provide a survey map. FBG based accelerometers interrogated with the tunable laser interrogators have been proposed [6] and demonstrated for seismic measurements [7].

Recently we have demonstrated an optical seismic measurement system using FBG based seismic sensors (accelerometers 21030-11 and 21040-08) designed by Fugro [6,7] and interrogated using our tuneable laser-based interrogator which was installed in a field and measured side by side to commercial electronic geophones (Geophone 1, Geophone 2, Lennartz) as shown in figure 4 (middle). The PSD (left) and time plot (right) in figure 4 shows the correlation between the optical and electrical seismic measurements with both systems picking up the same events. The sensitivity of the optical accelerometer was ~1nm/g and was measured with the interrogator sweeping at 8kHz, while the electrical sensors were measured using a commercial seismic recorder sampling at 4kHz. It should be noted that the optical measurements did not suffer from the high pass filtering that the electrical sensors exhibited as shown in the PSD plot in figure 4 (left).

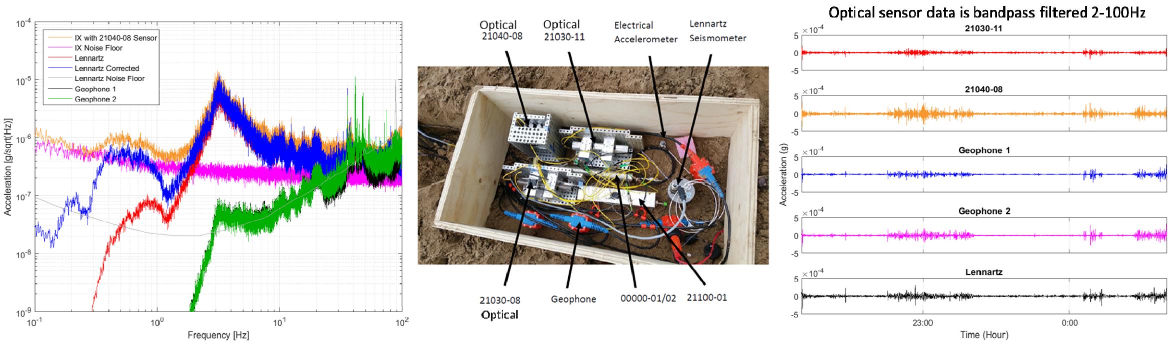

Fig. 4. Field test of electrical (Lennartz, Geophone 1, Geophone 2) and optical (FBG based sensors 21030-11 and 21040-08) seismic sensor measurements and noise floor on a frequency PSD plot (left), and time series plot (2.5hrs) (right).

4. Conclusions

Here we have developed and demonstrated a tunable laser based FBG optical interrogator using a Silica PLC based PIC and an InP based electronically tuneable laser sweeping at kHz sweep-rates, with <20fm wavelength repeatability (1σ over 10 seconds), <±1pm absolute wavelength accuracy (P2P measured using a gas cell), <30fm long-term wavelength precision (1σ over 12 hours), and low noise floor over 0.1-500Hz bandwidth delivering >120dB dynamic range signal measurements. We also demonstrate how high performance electronically tuneable laser based FBG optical interrogators when combined with high sensitivity FBG based accelerometers (1nm/g) can provide low noise seismic measurements in the sub Hz (down to DC) to 500Hz signal bandwidth.

5. References

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