EXTREME FIBER SENSING CAPABILITIES FOR COMPOSITE MATERIALS IN AEROSPACE

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Abstract
This work describes the use of a high-speed fiber optic interrogation unit based on integrated photonics in structural health monitoring. It overcomes the limitations of other high-speed interrogators with respect to dynamic range by employing a small scale demultiplexed interferometer. The interferometer is combined with another chip based interrogator that accurately determines absolute wavelength of fiber Bragg gratings at a lower sampling frequency. This combination, which we named SuperGator, is used together with a broadband light source to interrogate multiple sensors simultaneously. With experiments executed with a sensor bonded to an aluminium plate, we demonstrate that the system is suitable of sensing high frequency disturbances as encountered during lamb wave testing. Moreover, the superior dynamic range of the interrogator is indicated, which makes it suitable for monitoring extreme dynamic loading events.

1. Introduction

One of the biggest challenges for the aircraft industry is the reduction of environmental impact as well as operational costs of flight services. New materials such as composite structures have to be introduced to lower weight and expenses in manufacturing and maintainance [1]. Aircraft materials are exposed to extreme dynamic loading during operation, which may affect the lifetime of components and the safety of the aircraft. The EXTREME Dynamic Loading project within the Horizon 2020 framework is focused on enabling the design and manufacturing of reliable composite material products for aviation. This includes the development of novel methods for Structural Health Monitoring (SHM).
Electrical strain gauges (ESG), piezo-electric sensors (PZT), and Fiber-Bragg Grating (FBG) are commonly used SHM techniques. While ESG are good at accurate determination of strain, they are susceptible to Electro Magnetic Interference (EMI), which limits their bandwidth. Piezo-electric sensors on the other hand are sensitive to high frequency disturbances but are generally unable to perceive permanent strain of the test subject. As PZTs require electric wiring they are also subject to EMI.
FBG sensors are capable of measuring static and dynamic strain. The bandwidth of the sensor is limited by its length as the transfer function approaches zero when the wavelength of the strain wave is of the same size as the FBG [2]. Moreover, they are small in footprint and not affected by EMI.
Common fiber optic interrogators are limited in precision by the radiant energy collected from a sensor. Special interrogation systems are needed to achieve the required sensitivity for strain waves at high sampling rates. Wild and Hickley [3] reviewed the high speed interrogators for FBG in acoustic sensing. The presented methods use filter systems that are tuned to the wavelength of the FBG in order to maximize the response of the interrogator to any wavelength shift. Transmit reflect detection is introduced using a laser tuned to one of the flanks of the FBG and analyzing transmitted as well as reflected light. Even though a high sensitivity is reached the dynamic range of the interrogator is limited by the FWHM of the FBG. Stan et al. [4] managed to increase the range of edge-filter interrogators

using a control loop for tuning of the filter. A maximum range of 450 με was demonstrated. However, the disadvantage that tuning of the optical filter is required remains. Monitoring an FBG array with several sensors demands multiple control units and filters implying significant complexity and hardware costs.

Therefore, we present a high speed Photonic Integrated Circuit (PIC) based interrogator with a large dynamic range and no need for adjustment to the sensor. The interrogator comprises two units. The first utilizes a Mach-Zehnder-Interferometer (MZI) and a Arrayed Waveguide Grating (AWG) which are both integrated on a chip. The second unit is a standard PIC-based Technobis tft-fos interrogator used to determine the absolute wavelength of several FBG sensors. Their combination results in the so called SuperGator, a small footprint optical interrogator capable of measuring static and dynamic strain in multipe FBGs.

2. Fiber optic sensing with the SuperGator

2.1. SuperGator interrogation principle

The SuperGator is a combination of two devices to produce a high-speed interrogator that measures absolute wavelength with a large dynamic range. A Technobis Gator is used to determine abosolute wavelength of one or several FBG sensors at a sampling speed of 1kHz. It is build around an AWG that distributes the FBG signal onto several photodiodes. The central wavelength of the reflected spectrum is calculated by a Center Of Gravity (COG) algorithm [5] and serves as a reference for the wavelength determination via the MZI.
The MZI is a 3-path interferometer, where each path is shifted in phase by 2/3π. An AWG splits the output of the MZI into six different channels. Together AWG and MZI form a De-Multiplexed Interferometer (DMI). Both, DMI and the optical interrogation unit of the Gator, are each integrated on an application specific optical chip.
The response P_i for each photodiode of a 3-path interferometer is governed by [6]:

$$P_i(\lambda) = A(\lambda)\left(1 + V\cos\left(\Phi(\lambda) + (i-1)\frac{2\pi}{3}\right)\right). \tag{1}$$

A is the amplitude, in our case the transmission of the input signal through the AWG, V is the visibility of the MZI, and Φ is the phase of the MZI, which is determined by the Optical Path Difference (OPD) of the interferometer and therefore wavelength dependent. Fig. 1 displays the ideal photodiode response curves for three channels that are almost completely separated in wavelength.
With the 3-phase algorithm the wavelength dependent phase can be calculated as:

$$\Phi = \text{atan}\left(\frac{\sqrt{3}\,(P_2 - P_3)}{2P_1 - P_2 - P_3}\right). \tag{2}$$

As it is an invertible function between -π/2 to π/2 it can be used to determine the wavelength if the dependency $\Phi(\lambda)$ is known. This phase curve can be gained by recording a wavelength scan of a narrow bandwidth scanning laser with the DMI.

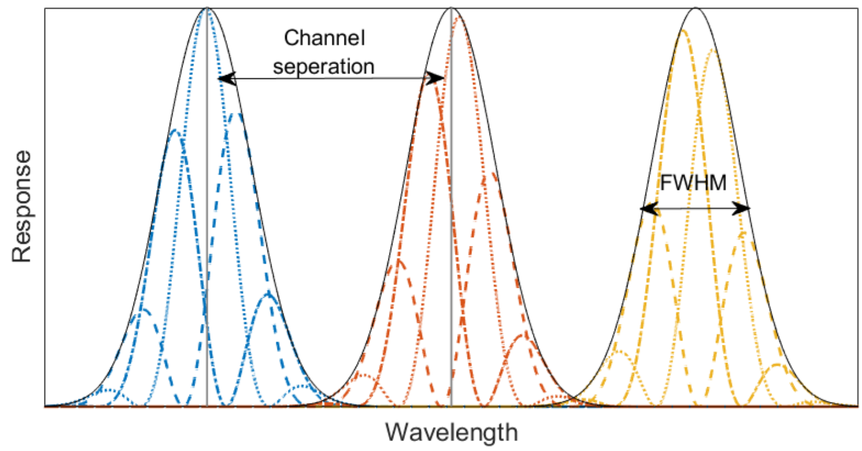

Figure 1. Illustration of a typical DMI response curve of three different channels and the envelope function of the AWG ($2A(\lambda)$) is shown in black. The FWHM (typ. 1nm) and the channel separation (typ. 2nm) of the AWG are illustrated here.

Fig. 2 illustrates the setup used for high speed interrogation. A broadband SLED sends light through a circulator into a fiber equipped with three FBGs. The light reflected by the FBGs is directed towards the wavelength detection system, where it is split between Gator and DMI. While the Gator directly measures central wavelength at a frequency of 1kHz, the DMI yields phase values at 1MHz (Eq. 2).

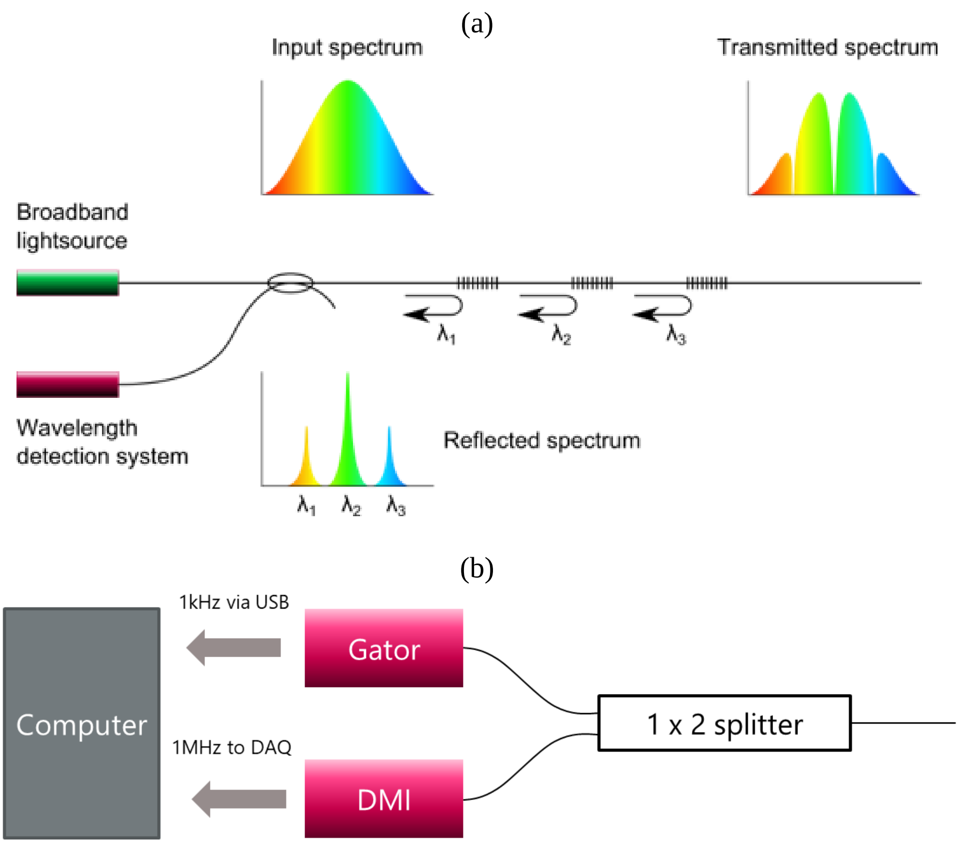

Figure 2. Principle of FBG interrogation (a). Wavelength detection system with Gator and DMI(b).

2.2. High speed interrogator prototype

The wavelength detection system consists of the Gator, an off-the-shelf solution for fiber optic sensing based on an AWG integrated on a PIC, and a prototype DMI unit dedicated to the Extreme project. The photodiode output of the DMI is amplified by a two-stage low-noise amplification circuit to an amplitude of several volts. This signal is recorded by a Data Acquisition Card (DAQ) from General Standards. The 66-18AI32SSC1M samples 32 channels at 1MHz and 18 bit resolution. The input range was set to ±5V.
A Thorlabs SLD1550P-A40 was used together with a CLD1015 to ensure high power illumination in a wavelength range from 1540-1560nm.
A custom high reflectivity FBG array from Techica with three sensors was used for testing. The sensors were carefully matched with the spectral response of the DMI and the Gator. Due to the small size of the sensors of 5mm length, high frequency waves of 300kHz can be detected in aluminium according to the sensitivity analysis performed by Minardo et al [2]. One FBG was bonded to an aluminium plate (41cm x 35.5cm x 0.3cm) with HBM X60 strain gauge adhesive.

2.3 Experimental results

2.3.1 Detection of lamb waves

Lamb waves are often used in SHM to determine structural damage from impacts [7, 8] as localized damages attenuate and reflect the waves. Betz et al even showed a method to determine the location of these disturbances with two rosette structures of FBG sensors.
We used a ultrasonic transducer from Physical Acoustics (WSA 100-1000kHz) to excite pulses in the aluminium plate. The transducer was placed such that emitted waves will propagate along the axis of the FBG. An Agilent 33522B function generator was used to create a 10V pulse of 22kHz bandwidth centered around 248kHz. The Gaussian shaped pulse was repeated every 10ms over a period of 10s. Propagating through the plate it was first picked up by the FBG at 11cm from the source before it reaches another ultrasound transducer alike the sender at 16cm distance. The signal of the PZT and the pulse driving the sender were measured by a Picoscope 6402A.
Figure 3 displays the pulse generated by the function generator, the measured wavelength shift of the FBG by the DMI and the signal picked up by the PZT. The DMI measurement was first averaged over 1000 pulses and subsequently a bandpass filter was applied that removes contributions outside the frequency range of the input signal (237-259kHz).

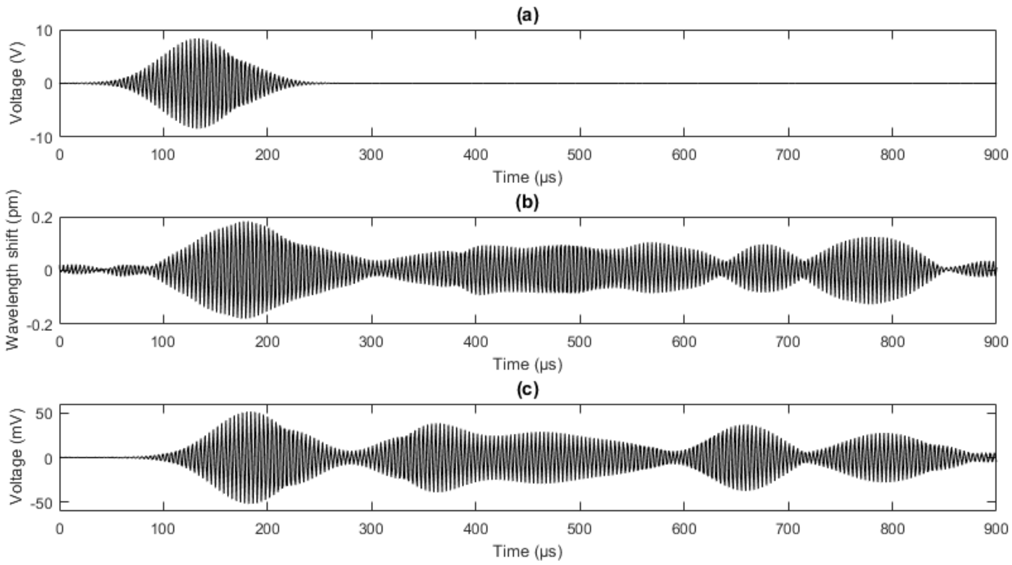

Figure 3. Demonstration of Lamb wave detection. (a) Gaussian pulse generated by function generator. (b) Wavelength shift of FBG measured by DMI. (c) Signal of PZT receiver.

The DMI measures a wavelength shift with an amplitude of 0.2pm compared to 50mV measured by the PZT. The general shape of the pulsed wave is preserved. Due to the different location of both sensors on the plate, it is difficult to compare the signal after the first pulse passing through the senors, which ends after approximately 300μs. Further upcoming pulses are reflections of the pulse that propagate in a direction not aligned with the axis of the FBG.

We determined the velocity of the pulse by cross-correlating the input pulse with the measured signal and received the following values:

$$v_{T6} = 2619\frac{m}{s}, \quad v_{PZT} = 2963\frac{m}{s}. \tag{3}$$

2.3.2 Dynamic range testing

To determine the strain applied to the FBG, a Kyowa strain gauge (KFG-5-120-C1-23) was attached parallel to the FBG. The strain gauge was read-out by a NI-DAQ card (NI9219). Strain was calculated from wavelength shift by a calibration graph (Fig. 4). The calibration was gained from a measurement of three static strain levels with Gator (FBG) and strain gauge.

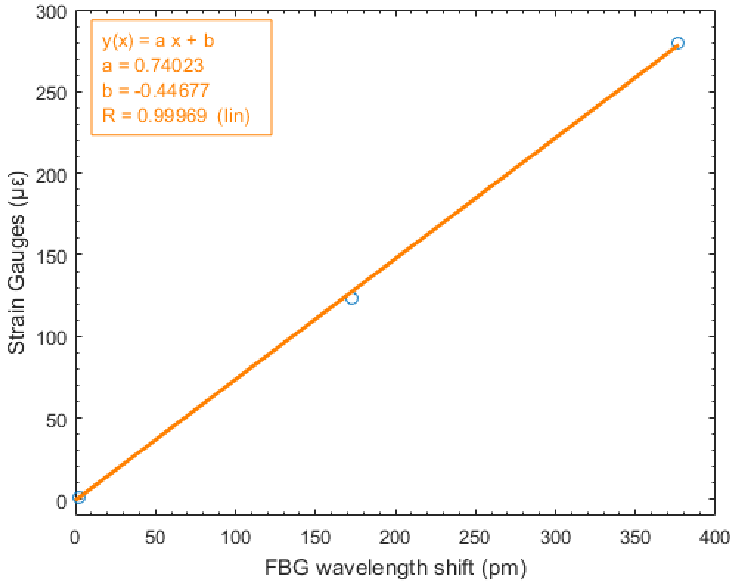

Figure 4. Calibration graph of FBG for strain measurement.

The dynamic range of the system was illustrated by manually applying strain to the FBG bonded to the aluminum plate. Fig. 5 displays how the measured strain develops over a range of 1,100με. As a reference we use the strain calculated from the calibrated Gator measurent sampled at 1kHz. Although significant deviations are visible, the strain measured by the SuperGator stays close to ±10% devation for more than 500με. The area from 600 to 800με forms a blind spot of the SuperGator where wavelength is not well defined. Above this range the SuperGator measurements and reference come together again.

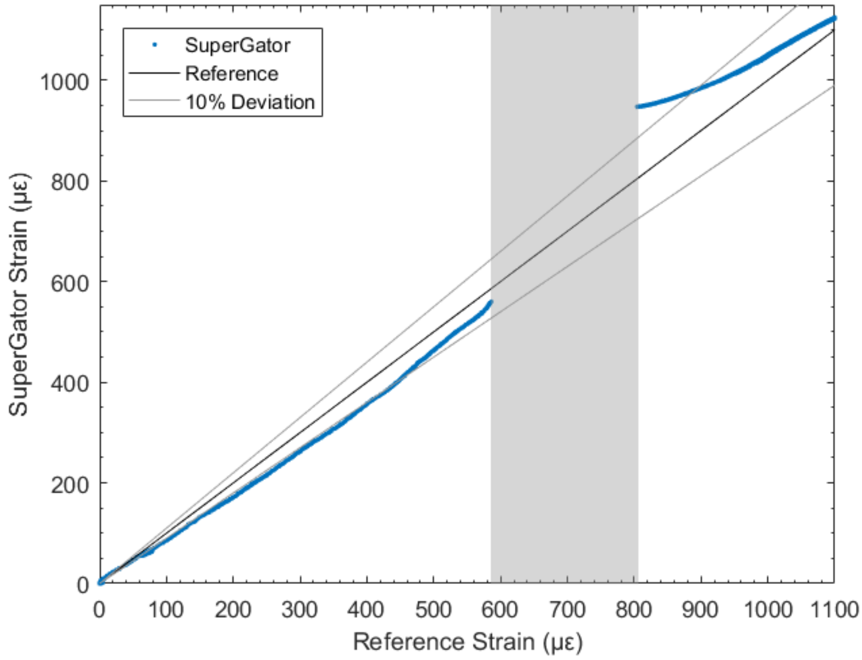

Figure 5. Strain measured by SuperGator versus reference strain. The measurement is compared to a linear reference. The gray area indicates a blind spot where SuperGator wavelength measurement is not well defined.

3. Discussion

A high speed interrogating system based on an integrated MZI was demonstrated. Lamb waves testing showed the system is capable of sensing ultrasonic waves of 250kHz frequency with only 0.2pm amplitude, which proves the resolution of the system is smaller than 1pm while using 1MHz sampling frequency.

Veloctiy of the pulse was determined and compared to a PZT measurement. The 13% difference between the two measured velocities can be caused by a synchronization error, as different data acquisition devices were employed for each sensor, or the width of the pulse, which is larger than the time the pulse required to travel through both sensors. Better accuracy can be achieved here by applying a shorter pulse at an higher amplitude. Generally, the PZT transducer can be exposed to more than 100V but a suitable high frequency amplifier is needed to generate such a pulse.

Moreover, we showed that a dynamic range of 1,100µε can be achieved. There are several explanaitons for the observed mismatch between the strain measurements shown in Fig. 5. The most likely one is the presence of two additional sensors that create background which impacts both Gator and DMI.

The gap between 600 to 800µε can be explained by the response of the DMI as shown in Fig. 1. With increasing strain the wavelength shifts into an area, where the response is small. Any background, crosstalk, or other imperfections of the device heavily influence the measurement. Therefore no decent wavelength determination is possible in that range.

For full coverage of a large dynamic range (e.g. 5,000µε) a different AWG design is required. Suitable designs are commonly used for Technobis Gator systems; however, the chip designer always has to make a choice between dynamic range and the number of sensors that can be monitored.

4. Conclusions

We demonstrated the feasibility of a 1MHz fiber optic interrogator with a resolution smaller than 1pm and a dynamic range of more than 1,000με capable of simultaneous monitoring of three sensors. The presented system adds to common SHM strategies due to its large bandwidth and dynamic range. Therefore, it is suited for extreme loading scenarios commonly encountered in aviation. It overcomes the limited range of edge-filtering techniques and uses a broadband light source, which requires no wavelength tuning.

Further evaluation of the tool is planned within the EXTREME project. The interrogator will be used together with an FBG array bonded to a composite plate. Impact testing is planned for later this year. A interesting application for the presented interrogator is certainly the damage location with FBGs and lamb waves [8].

Acknowledgments

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