Dynamic Strain Measurements by Fiber Bragg Gratings and a 100 MHz Dispersive Spectrometer

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***Abstract*—We present dynamic optical strain measurements on a metallic cylinder asymmetrically loaded by explosives bands using 24 fiber Bragg gratings distributed along three fibers. The 100 MHz dispersive spectrometer reveals resonances without any electromagnetic perturbations compared to slower electrical strain gauges.**

Keywords— Fiber Bragg Grating, Spectrometer, Dynamic strain experiments.

I. INTRODUCTION

New materials implemented in complex structures require as well dynamic experiments with high frequency diagnostics to optimize either the materials or the structure's design. In few defense applications, structures can be intensely loaded within a very short time by a blast or an explosive directly in contact. New materials are also studied by isentropic compression under high pulse powers where large strains and high strain rates are generated under intense magnetic field-driven Laplace forces [1]. Strain levels are classically measured by Electrical Strain Gauges (ESG) [2], which are about few hundreds µm thick and ≈ 100 mm² in area. Such a sensor is limited in bandwidth to few hundreds of kHz and is sensitive to electromagnetic fields (EM). Alternatively, optical fibers with Fiber Bragg Grating (FBG) sensors are immune to EM environments. FBG sensors can be multiplexed in wavelength along a single fiber, which is itself very light thanks to the small fiber diameter. They are used for decades to monitor strain in structural health monitoring but commercial interrogators are typically available at a rate of a few kHz, very rarely above 100 kHz. In dynamic strain experiments, spectra acquisition rate must be at least one order of magnitude higher (>1 MHz).

One approach to perform FBG interrogation at a few MHz rate is the use an edge filter, realized with a "triangular" Chirped FBG, to convert the FBG's sensor wavelength into an optical power level [3]. CEA also demonstrated such a system, at 10 MHz acquisition rate, with two crossed FBGs glued onto ring Aluminum samples in isentropic compression experiments [4]. To multiplex many FBGs on the same channel (fiber) and increase the acquisition rate to 100 MHz, a "dynamic dispersive interrogator" can be used. The LANL initiated this approach in 2015 [5] for shock sensing. Since, CEA regularly published results [6-8] for detonation speed measurements (5-8 km/s) and shock pressure measurements (1-6 GPa). This high speed spectrometer is internally called *BraggPulse*. First strain measurements with the *BraggPulse* system were for *in situ* monitoring of carbon/epoxy laminates exposed to a blast loading [9]. Three FBGs were inserted between two plies before the curing process and were then directly used during the blast experiment. In this paper, we increased the sensor density per fiber to 8. We will illustrate that the raw optical spectrogram obtained needs to be corrected by temporal shifts. Finally, the system was validated on metallic ring and cylinder structures asymmetrically loaded by explosives bands. The results are compared to signals obtained from ESGs.

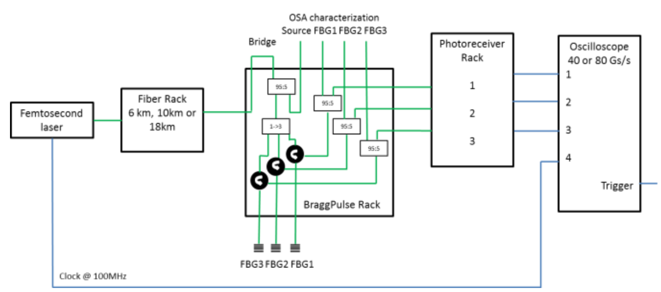

Fig. 1. Three FBG dynamic dispersive interrogator systems sharing the same wavelength to time conversion stage (*BraggPulse* system).

II. BRAGGPULSE SYSTEM AND THE SENSORS SERIES

The *BraggPulse* system is described in Fig. 1 and details can be found in [6-8]. The concept is based on a modelocked laser source with a wide optical spectrum; the repetition sets the interrogation rate (100 MHz). The reflected FBG spectra series are converted into time using chromatic dispersion. In the following experiments, the three channels were recording on a 80-GSa/s oscilloscope. To cover all the FBG wavelengths, the SMF28 fiber was 10 km long. The span was then 58.8 nm for a resolution is $\approx$74 pm as there is 800 points by optical spectrum every 10 ns.

The fibers used have 8 FBGs, 2-mm-long, positioned every 25 mm with wavelengths peaks from 1535 to 1570 nm with 5-nm spacing. The fibers are recoated with polyimide and were glued at room temperature onto the metallic cylinder. In the

BraggPulse system all spectra are multiplexed in time by chromatic dispersion but each FBG signal needs to be processed separately to compensate the forward and back travelling time between the first FBG and the others. These delays can be characterized using an optical backscatter reflectometer like the OBR LUNA 4600.

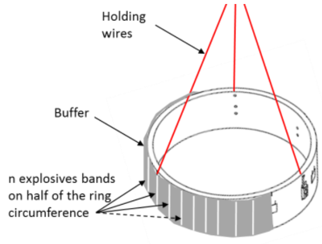

Fig. 2. Sketch of an experimental setup in the case of a ring sample.

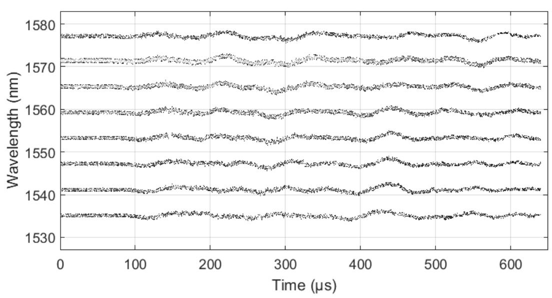

Fig. 3. 2nd fiber (vertical) raw spectrogram recording with the *BraggPulse*.

III. Dynamic experiment

One of the goals of the experiment was to measure dynamically the strain levels in many points of a metallic cylinder of about 180 mm in diameter and 660 mm in height submitted to an asymmetric load by *n* explosives bands, all attenuated by identical buffer layers. A similar setup, in the case of a ring with the same diameter, is sketched in Fig. 2. The cylinder is hold by wires to be free of movements, like a pendula, which allows quantifying the mechanical loading. The 1st fiber was glued horizontally on the top inner side of the cylinder with explosives and buffers just behind the metal surface. The 2nd fiber was placed outside and vertically centered in height and angle on the side without explosives. The 3rd fiber was placed outside the cylinder and at the bottom side without explosives. A 4th fiber was also placed in parallel to the 3rd one and was connected to a commercial FBG interrogator from IBSEN Photonics with a recording rate of 19 kHz. 26 reference ESGs from [2] equiped the cylinder and were recorded at a rate of 1 MHz with a 100-kHz low-pass filter in the conditioners.

From the *BraggPulse*, the 24 FBG measurements could be processed for the first 650 µs at rate of 100 MHz. The raw spectrogram of the vertical fiber is presented in Fig. 3. The 1535-nm FBG data is correct but all the other FBGs spectra need to be individually corrected in the time domain due to the travelling time between FBGs. Few FBGs can be fairly compared to ESGs as there are located in the same area. Two examples are presented in Fig. 4. The top graph is a comparison between an ESG and a FBG placed in the inner top part of the cylinder. We attribute the main first peak in the ESG signal to an EM perturbation from the nearby detonator which is not visible in the FBG signal. The behavior of both sensors is very close with the matching strain amplitudes and frequencies. Within the first 50 µs, the FBG sensor caught higher frequency features. The second comparison with two ESGs is in the middle of the cylinder and not perturbed by EM signals. Again, the FBG signal is very close with matching strain amplitudes and frequencies. The visible noise is mainly due to the thousand times higher recording frequency. The 4th fiber signals recorded at 19 kHz are almost identical to ESGs.

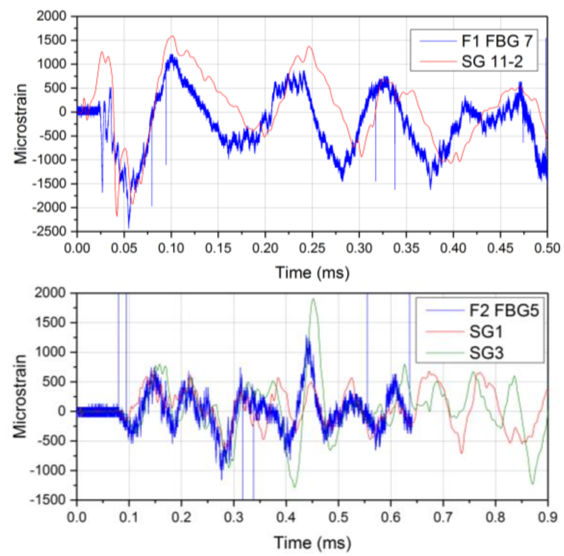

Fig. 4. Electrical strain gauges *vs.* FBG a) inside the cylinder and near the detonators b) outside the cylinder in the middle of height.

IV. Conclusions

We demonstrated the dynamic use of wavelength multiplexed FBG strain sensors with a 100 MHz interrogation system. 24 FBG sensors with only three optical fibers revealed higher frequency features masked by EM perturbation in the ESG signals and this is a great benefit in such experiments.

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