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Shocks Sensing by Fiber Bragg Gratings and a 100 MHz Dynamic Dispersive Interrogator

Y. Barbarin, A. Lefrançois, B. Rougier, F. Sinatti, O. Lassalle, A. Osmont and J. Luc
CEA, DAM,
F-46500 Gramat, France
yohan.barbarin@cea.fr

***Abstract* — A multi-channels high resolution dispersive interrogator with at a high sampling rate has been developed to measure shocks pressure levels by Fiber Bragg Gratings (FBGs). Two FBG orientations are compared numerically and experimentally. The first one is along the cylindrical target axis, thus the grating spectrum is "blue shifted". The second orientation is perpendicular to the target axis and the grating spectrum is "red shifted". The interrogator uses a femtosecond laser source to cover the C+L band spectrum. The source repetition rate (100 MHz) fixes the spectra acquisition rate. The wavelengths are basically converted to time using a long telecom fiber. The time-multiplexed spectra are recorded with 400 points by a fast oscilloscope (40 GSa/s). The experimental setup is a Tin plate impact on a PMMA target performed in a 35-mm single-stage gas gun. An impact at 510 m/s generates a pressure level of 1.69 GPa during 5 µs. The performance of the dynamic interrogator and the wavelength shifts in the two FBG configurations are discussed.**

Keywords — Fiber Bragg Grating, Shock, Spectrometer, Dispersion, High Energy Material

I. INTRODUCTION

New materials, alloys or assemblies are regularly characterized by shock experiments to adjust equations of state (EOS) and elastic-plastic behavior parameters. In shock experiments as well as in shock-to-detonation transition (SDT) of high (HE) energy materials, the *in-situ* progression of the pressure level is a very valuable input. It is classically measured electrically by piezo-resistive gauges [1-2] which are about 100 µm thick and few mm² in area. The piezo-resistive material and its resistance are swapped to cover several pressure ranges up to hundreds GPa. These types of sensors offer satisfactory response time (~100 ns) but the sensing area and the electrical connection are relatively wide and therefore intrusive. Also such a sensor is sensitive to intense electromagnetic fields (EM) which ban its use in shock experiments produced with high pulsed power generators [3].

Alternatively Fiber Bragg Gratings (FBGs) are immune to EM environments and can be as thin as 40 µm in diameter. They are used for decades to monitor strain in structural health monitoring (SHM). Commercial interrogators typically monitor many peak-wavelengths at a rate of a few kHz, very rarely above 100 kHz. In shock experiments, spectra acquisition rate must be at least two order of magnitude higher (>10 MHz) and such an interrogator is, to our knowledge, not available on the market.

By optimizing the integration of the fiber in the target material, the shock profile is well transmitted to the FBG. The wavelength shift is different when placing the FBG facing the shock or perpendicular to it. It was confirmed experimentally in [4] where the signals were acquired with few discrete optical filters. The LANL published many papers on this approach for shocks and detonation, the acquisition systems improved in resolution over the years [5-6] and lately a "dispersive spectrometer" was used [7-8]. Such fast spectrometers were previously reported for FBG interrogation under different names [9-11] but not for shock studies. The concept is based on a modelocked laser source with a wide optical spectrum; the repetition sets the interrogation rate. The reflected FBG spectra series are converted into time using chromatic dispersion. At CEA Gramat, we switched from an AWG–based dynamic spectrometer [12] to a dynamic dispersive spectrometer [13]. In this paper, we present a modified version to measure signals on 3 channels using the same wavelength-to-time conversion stage. The system is now a "dynamic dispersive interrogator" called "BraggPulse". In the following sections, we present simulation and experimental results with two FBGs integrated under two orientations in a PMMA target impacted by a Tin plate.

II. DYNAMIC FBG DISPERSIVE INTERROGATOR

A. *Shock pressure measurement by FBG*

By placing the FBG in the shock direction, the grating period reduces and the refractive index increases as function of pressure in the silica. The two phenomena are of opposite sign but the reduction of the grating period is dominant and at the end the FBG peak wavelength shifts towards the lower wavelengths as function of pressure [4]. We deeply studied this configuration theoretically for FBGs integrated in Aluminum targets [14] in the range of [0 – 4] GPa. The wavelength-shift to pressure dependency is not linear and depends on the target material. In Aluminum [14], the shock coupling to Silica is near 75% and wavelength-pressure slope starts roughly at -10 nm/GPa and it reduces as function of pressure.

By placing the FBG perpendicular to the shock, the grating period remains constant but the refractive index increases. As a consequence, the FBG's peak wavelength shifts towards the higher wavelengths as function of pressure [4].

The shock coupling to the fiber has been simulated using a 2D hydrodynamic code Ouranos in this case with PMMA target.

B. Dynamic dispersive interrogator

The dynamic dispersive interrogator is described in Fig. 1. The femtosecond laser is used as a source to benefit from its wide optical spectrum to sense the FBG and its repetition rate (100 MHz) which sets the FBGs spectra recording rate. The laser spectra are then stretched temporally in a long SMF28 fiber. This stage could be done with a twice shorter fiber thanks to a circulator and a faraday mirror but as we didn't experience any polarization issue, the simple fiber roll was kept. The signal is then split in three channels. The oscilloscope's 4th channel is now kept to measure the modelocked laser clock and later on more easily process the three time-multiplexed signals. In each measurement channel, the wavelengths are gradually sent to interrogate the FBGs. The fiber length fixes the span of the spectrometer; however it can be doubled or even tripled by wrapping the spectrum if the signal is easy to follow like a single wavelength peak. The 3 FBGs spectra are converted electrically by 38-GHz photoreceivers and recorded on either a 33-GHz oscilloscope with 80-GSa/s or a 16-GHz oscilloscope with 40 GSa/s. The sample rate determines the spectrometer resolution. For instance, with a 100 MHz modelocked laser and 18 km of SMF28 fiber, the measured span is 30.56 nm and the resolution is ~38 pm at 80 GSa/s or ~76 pm at 40 GSa/s. The oscilloscope bandwidth limits the stiffness of the side of a FBG spectrum but it is typically not an issue. In Fig. 2, the time-wavelength relation was measured over 70 nm for 2 channels of the BraggPulse system by adding a tunable filter between the wavelength-to-time conversion stage and the 1x3 coupler and by placing fiber mirrors instead of FBGs. For each wavelength, 20 measurements were recorded on a period of 200 ns. The fits are done using a quadratic function for more accuracy but the curves are very close to linear and to the SMF28 dispersion value near 1550 nm (17 ps/nm.km).

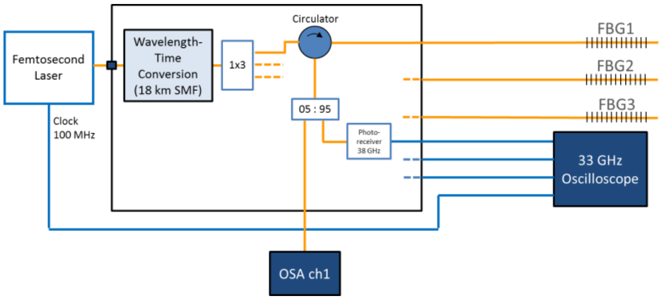

Fig. 1. Three FBGs dynamic dispersive interrogator system sharing the same wavelength to time conversion stage ("*BraggPulse*" system).

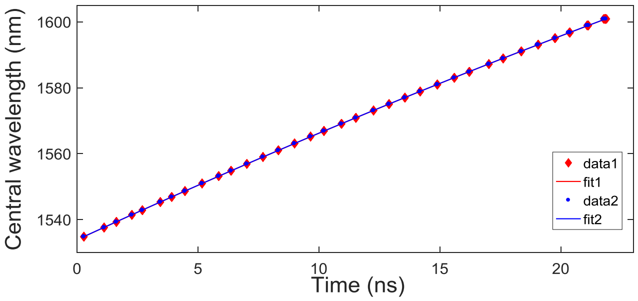

Fig. 2. Characterization of the time-wavelength relation for two channels of the BraggPulse system covering 2.2 periods of the modelocked laser.

C. Design of the experiment

The experiment is an impact of a 10-mm thick Tin plate on a 14-mm thick PMMA plate. The experiment is performed in a 35-mm in diameter single-stage gas gun facility. The pressure is consequently maintained over 5 µs. In the center of the target (Fig. 3), a hole of 0.8 mm in diameter allows inserting the first FBG which is 2 mm long and centered at 1597 nm. The second FBG is perpendicular to the shock, and placed 8 mm from the surface and 3 mm from the center. FBG2 is also 2 mm long but centered at 1540 nm as a red shift is expected. Each FBGs are connected to a different measurement channel of the BraggPulse. The fibers are 125 µm in diameter and have been glued in Silica capillaries to ease the integration in the target. The capillaries have an internal diameter of 150 µm and an outer diameter of 0.55 mm. The thin glue layers have not been taken into account in the following hydrodynamic simulations.

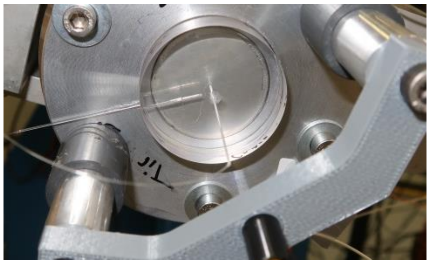

Fig. 3. Image of the PMMA target with 2 FBGs in different orientation. The FBG's fibers are glued in thin capillaries with an external diameter of 0.55 mm to ease the target drilling.

D. Simulation and Experimental results

For this experiment, the impact velocity was measured to be (510 ± 10) m/s by optical barriers. We can deduct from this velocity and EOS a shock level of (1.69 ± 0.03) GPa. According to our 2D hydrodynamic simulations (Ouranos code, Fig. 4), the average pressure level in the fiber's core (2.00 GPa) is ~18% higher than near the PMMA interface and the pressure profile shows oscillations in the shock front with a peak at 2.85 GPa. These oscillations are almost negligible at the Silica-PMMA interface. FBG1 senses over the two first millimeters of PMMA. FBG2 senses at a depth of 8 mm and it is almost of single point measurement over time as the shock front is planar. This FBG measures very nearly the same pressure over its 2-mm length. As the speed of sound in Silica is higher than in PMMA, there is a "precursor" in the fiber profile of Fig. 4. This is not as strong for FBG1 as it is at the beginning of the shock and not seen at all by FBG2.

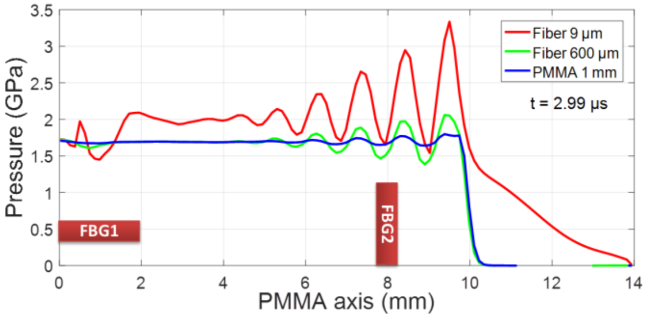

Fig. 4. Simulated pressure profiles at 2.99 µs at different distance from the longitudinal axis. The two FBGs positions are shown.

The experimental signals are demultiplexed from the time domain and converted to wavelength numerically using the curves of Fig.2 and plotted for both orientations in Fig. 5. The simulated average pressure over FBG1 and the punctual pressure level in FBG2 as function of time are also plotted and scaled linearly to overlap in amplitude the experimental data. FBG1 experiences a strong blue shift which is larger than the span. The spectra have thus been unwrapped once and the redundant parts hidden for more clarity. The measured maximum wavelength shift is -45.0 nm for the averaged peak and -40.1nm for the pressure plateau between 373.6 and 375 µs. The wavelength-pressure ratio is about -23.7 nm/GPa for the probed PMMA. It is 1.7 times higher than expected [4]. The shock level is maintained for 4.5 µs with a small reduction in the wavelength shift compared to the numerical simulations.

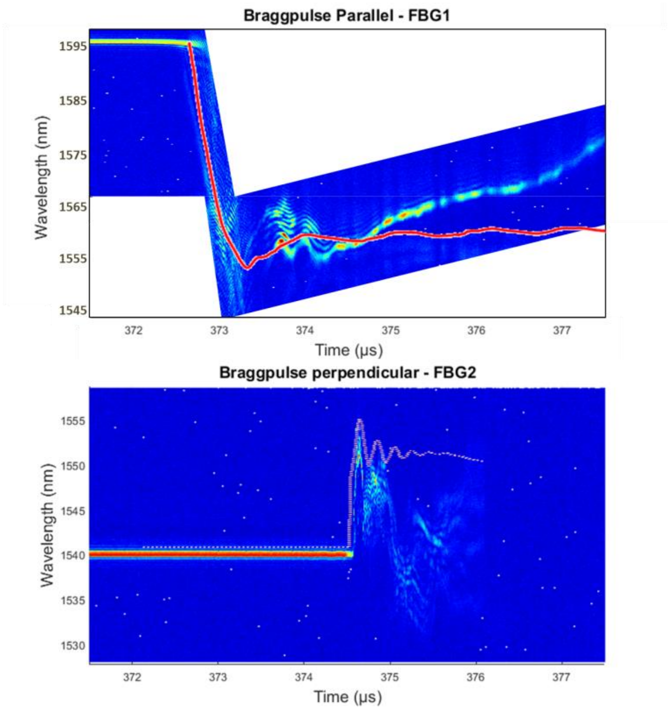

Fig. 5. Time evolution of the two FBGss' spectra measured by the BraggPulse for an impact at 510 m/s of a Tin impactor on PMMA. For FBG1 it covers two spans. The simulated pressure levels curves have been superimposed; for FBG2 it is slightly shifted upwards.

The second FBG experiences the shock 2.4 µs later. A maximum wavelength shift of +12.9 nm is observed at the first peak which is in agreement with our simulations. Then, the average wavelength shift between 374.7 µs and 375.0 µs is 8.0 nm and corresponds to a ratio of +4.7 nm/GPa with the shock in the PMMA target. This value is twice lower than reported in [4]. The shock is maintained only 0.40 µs which corresponds to the shock reflection time in the 550-µm thick Silica (fiber + capillary). Above this time, a 3D hydrodynamic simulation would be required to fully resolve the pressure level in the FBG.

III. CONCLUSIONS

Dynamic measurements of FBGs spectra in two orientations were recorded by a dispersive interrogator at a rate of 100 MHz in a shock experiment. The interrogator provides spectra every 10 ns with a resolution 76 pm at 40 GSa/s over 30.56 nm. We demonstrated that the span could be doubled if the by unwrapping the spectrum. The integration of the FBGs was eased in targets by using Silica capillaries of 550 µm outer diameter. The longitudinal FBG seems to resist to the maintained shock level but the wavelength shift, -23.7nm/GPa, is higher than expected. To follow the shock front and to get more resolution, we recommend using a slightly chirped FBG like in [12-13]. The perpendicular fiber can sense the shock for a limited time because the shock travels back and forward in the Silica, which can also damage it. The measured wavelength shift, +4.7 nm/GPa, is a bit lower than expected; nevertheless this would facilitate measurements of higher pressure levels in the C+L band. A theoretical study on the shock coupling like in [14] for Aluminum should be performed to fully discuss the wavelength shifts function in both configurations in the case of PMMA.

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