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Real-time, distributed measurement of detonation velocities inside high explosives with the help of Chirped Fiber Bragg Gratings

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ABSTRACT

Following the pioneering work of the Lawrence Livermore National Laboratory, Chirped Fiber Bragg Gratings are investigated as *in situ*, real-time, wavelength-position discriminators for measuring detonation speeds inside explosives.

Keywords: Fiber Bragg Grating, chirped grating, detonation velocity, explosive.

1. INTRODUCTION

Validation of initiation/deflagration/detonation models of Energetic Materials (EMs) is required as support for manufacturing to improve their design and to qualify both vulnerability and aging. Experimental techniques that measure a continuous change in detonation velocity provide insight into initiation and transient phases of deflagration/detonation processes. The detonation pressure is often estimated from the measurement of the detonation or interface velocities. Distributed measurements of shock or detonation velocities inside High Explosives (HEs) or propellants are therefore of prime importance. Shock waves travel at velocities of 2-8 km/s (2-8 mm/ μ s). The shock may be whether unsustained or maintained during several microseconds depending on explosive assembly and the shock front lasts \sim 10 ns. Sub-millimeter velocity measurement techniques require high-bandpass acquisition rates. For instance, for a velocity of 8 km/s, a minimal sampling rate of 10 MHz is required to achieve a spatial resolution of 0.8 mm. However, oversampling (at GHz rates) is usually performed to observe the shock front and also to improve the signal-to-noise ratio (SNR). Conventional velocity monitoring techniques involve streak cameras, contact pins or resistive probes. While streak cameras do not provide *in situ* measurements, the other probes provide local measurement (poor spatial resolution) and are intrusive (change in shock impedance). Optical fibers are miniature *in situ* probes that provide high measurement capacity in the purpose of detecting early transient phenomena. Three methods are often used: Drilled fibers (DF), Photonic-Doppler Velocimetry (PDV) and Chirped Fiber Bragg Gratings (CFBG).

The first method makes use of multimode PMMA fibers that are aligned in parallel with the detonation orientation. Holes are drilled within each fiber, separated by a pitch of 0.8 mm (8 to 10 holes). As the shock wave progresses along the fiber, ionization light is produced inside air holes and collected back by the fiber up to a photo-detector placed away. Since the pitch is accurately known, the measurement of transit time from one hole to another provides an estimation of the average detonation velocity (uncertainty is typically of several %). Spatial resolution and capacity are limited.

The second method was developed at the Lawrence Livermore National Laboratory (LLNL, USA) [1]-[2]. It takes profit of the large increase in refractive index (about 0.4 to 0.5) that occurs within the fiber part under compression by the shock wave. The optical interface moves along fiber axis at the velocity of detonation. The principle of the PDV technique is to record the interference signal between a reference light and the probe light that is reflected and Doppler-shifted by the moving interface. High-bandwidth photo-detectors and digitizers are used (a velocity of 1 km/s generates a beat frequency of 1.29 GHz at 1550 nm). However, the small amount of light (10^{-4}) that is reflected back leads to a poor interference contrast and only detonation events faster than the speed of sound in silica (\sim 5 km/s) may be detected. In this case, the optical interface being concave reflects light. For lower detonation velocities (2-5 km/s), the interface is convex and light is lost. In this case, the PDV technique requires to use special light guides such as Teflon tubes filled with aqueous solution of CsCl [1] (sound speed \sim 2 km/s). However, the simplicity of the method is lost.

The third method, also developed at the LLNL by J. Benterou [3], is based on a CFBG as wavelength-position discriminator, commercially available as dispersion-compensating device.

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As the fiber is progressively destroyed by the detonation wave, the shock interface is localized within the Fiber Bragg grating with the help of a wavelength-to-position transfer function. A spectrometry of the Bragg cut-off wavelength would thus yield the position of the shock interface. In practice, however, usual spectrometric devices do not operate at rates high enough and a high-frequency (GHz) spectrum-to-intensity conversion technique is used instead. It provides high SNR, excellent spatial resolution and may be used at any detonation velocity. In this work, the optical experiment and its calibration method are described and results obtained with CFBGs and DFs are compared.

2. EXPERIMENT

2.1 Experimental setup

Custom-made CFBG were bought from Redfern Optical Components (length: 50 mm, slope: 0.3 nm/mm, Full-Width at Half-Maximum (FWHM): 15 nm, mid-wavelength: 1545 nm, grating reflectivity: 99 %). The experimental setup is depicted in Fig. 1. It is similar to the one described in [3]. Light from a broadband erbium-doped fiber source (Amplified Spontaneous Emission (ASE), 15 dBm, [1530-1562 nm]) is launched into the port #1 of a 3-port circulator. Light exiting from port #2 is sent to the CFBG under test. The light reflected back by the CFBG goes back to port #2, exits through port #3 and is eventually splitted by a 50 % coupler. One arm provides a reference output while the other one is connected to a second CFBG (of same spectral characteristics) which purpose is to filter out extra light generated by the explosion. The signal filtered out by this CFBG is then sent to an InGaAs photodiode mounted in transimpedance circuit (HCA-S Femto, 3 dB-bandwidth = 400 MHz, conversion coefficient = 5 V/mW, linearity range = [0-1V]). An optical fiber attenuator is placed before the HCA-S device to adjust the output voltage to 1 V before testing. Finally, the output voltage is recorded by a LeCroy Waverunner 6100A oscilloscope (bandwidth = 1 GHz, maximum sample rate = 5 GS/s), triggered in time by the pyrotechnic board.

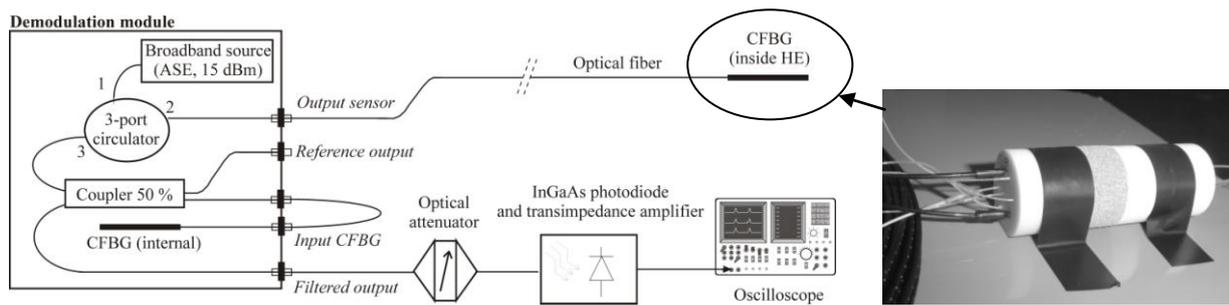


Figure 1. CFBG-based wavelength-to-intensity setup for detonation velocity measurements. On right side: view of the HE assembly (the CFBG was located at the center while DFs were aligned along several holes placed on a diameter of 15 mm).

2.2 Calibration of CFBG as wavelength-position discriminator

The amount of light that is reflected back by the CFBG is a linear function of the integral over the Bragg spectrum. The transfer function of the CFBGs must be calibrated prior to detonation experiments because, in practice, CFBGs exhibit a linear evolution (wavelength-to-position slope in nm/mm) in its central part only.

The CFBG was calibrated by a layer-peeling method. To do so, the CFBG was epoxy-bonded into a PMMA cylinder and polished gradually using a polishing machine. In this case, the polishing action progressed from the low-wavelength side up to the high-wavelength side. Adapted into an explosive assembly, the low-wavelength side of the CFBG must be put close to the booster (V401) so that the detonation wave moves in the same direction.

After each polishing step, the PMMA block was removed from the machine and its length, measured with a vernier caliper. Meanwhile, the optical signal reflected back by the CFBG and its Bragg spectrum were also recorded (Fig. 2). At the end of the experiment, the cut-off wavelengths were plotted with respect to distance. Since the light was filtered twice (by the CFBG under test and the CFBG placed inside the demodulation module), cut-off wavelengths are measured at $1/4^{\text{th}}$ of the amplitude. The wavelength-to-position slope is (0.35 ± 0.01) nm/mm and the useful length was shorter than expected (40 mm).

Finally, the signal transfer function was calculated by spectrum integration and plotted on Fig. 3-left. The signal measured while polishing the high-wavelength part of the CFBG actually superimposes very well over the theoretical curves. It is worthwhile to notice the nice reproducibility in the manufacturing of CFBGs. Therefore, the calibration achieved with a sacrificed grating may be confidently applied to others manufactured in similar conditions. This experimental transfer function (signal vs distance) shown in fig. 3-left is eventually transposed to yield the inverse transfer function (distance vs signal) shown in Fig. 3-right. Only the central part in the range [- 15 mm, 15 mm] is actually linear. The low-wavelength part (*i.e.* [- 25 mm, 15 mm]) is highly nonlinear and difficult to exploit. Optical signals are then converted into distance with the help of an adjusted inverse transfer function (Fig. 3-right) that actually covers a distance range of 37 mm [- 15 mm, 22 mm]) and is accurate to within ± 0.1 mm, according to residuals.

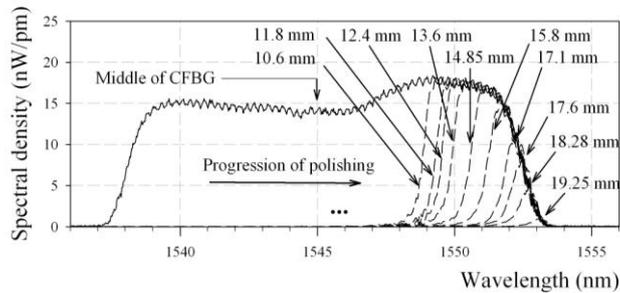


Figure 2. Calibration of the CFBG by the polishing method ("layer-peeling"). The polishing process progresses from the low-wavelength side up to the high-wavelength side. Interface positions (relative to the middle of the CFBG) are attributed to CFBG spectra observed after filtering by the CFBG inside the demodulation unit. Only the end of the process is shown for clarity.

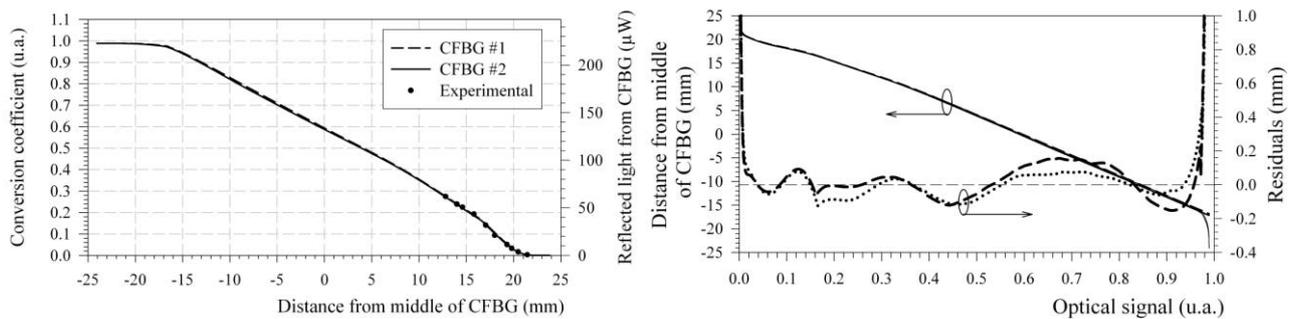


Figure 3. CFBG transfer function used for wavelength-to-position conversion. On left side: Calculated (line – left ordinate) and experimental (dots – right ordinate) transfer functions (signal vs distance). On right side: Inverse (transposed) transfer function (distance vs signal) and residuals between the experimental transfer function and its modeling.

2.3 Real-time detonation velocity experiments

CFBG were localized using an accurate local heating technique previously developed in our laboratory [4]. Then, a black paint was sprayed over the CFBG located inside the explosive. The CFBG was finally sleeved within a Teflon tube (diameter: 1 mm) and inserted at centre of the HE assembly along with DFs (Fig. 1). Three HEs (V401, PBXN109, B2238) were assembled in series (diameter = 30 mm; length = 20 mm; total length of assembly = 60 mm) with the aim to observe variations in detonation velocities.

Fig. 4-left shows the reference and filtered signals recorded during the explosion at a sampling rate of 1 GS/s and averaged by a factor of 10 (two HCA-S modules were used in this experiment). Both signals look very similar thus indicating that the optical contribution was in the C-band. The last peak is not understood at present time. Although no increase in optical signal is likely to happen, spurious light coming from the explosion may actually overlap within the C-band, in spite of black painting. The application of the inverse transfer function (Fig. 3-left) on the optical signals of Fig. 4-left yields the position diagram of Fig. 4-right. Discontinuities are observed at interfaces between the three explosives (at delay times 6.85 μ s and 9.7 μ s), accounting for shock transfer from one explosive to the other. Detonation velocities were estimated by a series of linear fits over explosive portions. Except for V401 (poorly covered by the

CFBG), the velocities are well recovered by the CFBG. The values are about 8.8 mm/ μ s, 7.25 mm/ μ s and 8.1 mm/ μ s for V401, PBXN109 and B2238 respectively. The most accurate measurement of velocity was obtained with B2238 ($\pm 0.7\%$ ($k = 1$) over [10 μ s, 10.5 μ s]). From the time evolution of the luminescence emitted by the DFs (Fig. 4-left), we obtained velocities of 8.8 mm/ μ s for V401 ($\pm 1.5\%$, $k = 1$) and 8.1 mm/ μ s for PBXN109 ($\pm 7\%$, $k = 1$). No signal was available for B2238. For PBXN109, the uncertainty in velocity measurement is larger than for V401 probably because of instability in the detonation process that conveys large uncertainty.

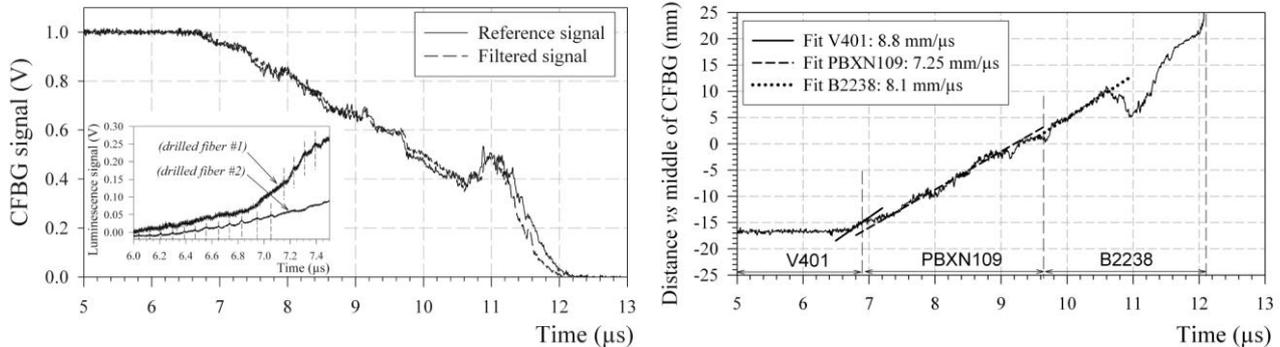


Figure 4. Optical signals recorded during detonation experiments. On left side: raw CFBG signals (inset: signals from DFs). On right side: Recovery of the time evolution of the shock interface after application of the inverse transfer function (fig. 3-right) and subsequent least-square fits.

3. CONCLUSION

Chirped Fiber Bragg Gratings (CFBG) provide high capacity, high SNR, distributed measurement of detonation velocities inside HEs. The time evolution of the shock interface is retrieved with the help of an inverse transfer function of the CFBG, adjusted prior to detonation experiments by the layer-peeling method using a polishing machine.

Detonation velocities measured by CFBG are in accordance with those measured by drilled fibers. However, since derivation is a noisy process, they were rather estimated by least-square fitting of the shock interface position with respect to time. A subsequent trade-off arises between spatial resolution and uncertainty in velocity measurement depending on oversampling. Under 1-GS/s sampling rate, the theoretical uncertainties in velocity are estimated at about $\pm 0.34\%$ and $\pm 11\%$ ($k = 1$) for a spatial resolution of ± 8 mm; ± 0.8 mm respectively. An increase in sampling rate up to 20 GS/s would lead to an improved uncertainty of $\pm 0.08\%$ and $\pm 2.3\%$ respectively.

The performance of the CFBG method was partly spoiled by spurious light generated by the explosion that superimposes over the useful signal (B2238). Furthermore, the uncertainty in velocity measurement may be related to heterogeneous structures of HEs (PBXN109). In this case, it would be interesting to investigate the correlation between signal oscillation and HE microstructure. Other experiments are planned with higher CFBG lengths and sampling rates.

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