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Chirped Fiber Bragg Gratings for Distributed Detonation Velocity Measurements

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Abstract: The accurate measurement of detonation velocity of high explosives is of fundamental importance in order to improve their design and manufacturing conditions as well as qualifying both vulnerability and aging. CEA LIST, CEA-Gramat and SAFRAN-Herakles are studying the performance of Chirped Fiber Bragg gratings for *in situ* distributed velocity measurements.

1. Introduction

The accurate measurement of detonation parameters (mainly detonation velocity V_D and pressure) of high explosives (HE) is of fundamental importance in order to improve their design and manufacturing conditions as well as qualifying both vulnerability and aging. *In-situ* velocity measurements are provided by electrical-shortening pins (ESP), drilled fibers (DF) or Photonic-Doppler Velocimetry (PDV) [3]. The uncertainty in velocity measurements is about $\pm 1.2\%$ for ESP, $\pm 2.1\%$ for DF and, for a liquid explosive (50 mm), an uncertainty of $\pm 0.3\%$ was obtained with the PDV method [1].

The improvement of current dynamic instrumentation is still challenging in terms of response time, accuracy and spatial resolution. Moreover, distributed measurements are desirable in order to monitor transient phenomena (*e.g.* Shock-to-Detonation - SDT). Fiber Bragg Gratings (FBG) are widely used as strain/pressure sensors in many applications (civil engineering, structural health monitoring, oil & gas, etc.). The wavelength-encoded signal provides reliable measurements even in harsh conditions. Their use in shock physics is motivated by the high-bandwidth, passive nature, electromagnetic immunity and small diameter ($\sim 150 \mu\text{m}$) of optical fibers minimizing perturbations due to impedance mismatch [2].

While usual FBGs are considered as point sensors (several mm long), chirped FBGs (CFBG) provide wavelength-to-position discrimination and enable to record velocity profiles over a range of 100 mm. As the shockwave progresses, the grating part within the shock is compressed and destroyed. Only spectral components arising from the upstream part of the grating (*i.e.* outside the shockwave) are observable in the spectral band of the interrogator restricted to the initial grating bandpass. A real-time spectrometry being costly and difficult to implement, the observed signal corresponds to the integral of this spectrum part from which shock front position is obtained thanks to a transfer function.

2. Experimental setup

The principle of the experimental device (BraggFast) is shown in Fig. 1 [3].

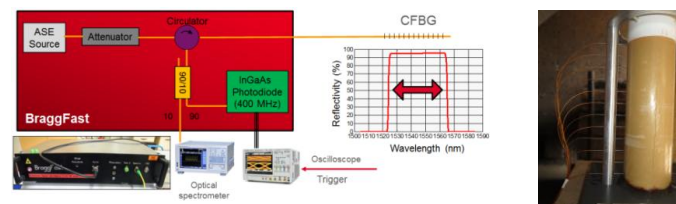


Fig. 1. BraggFAST measurement setup used for detonation velocity measurements with CFBGs (left) and explosive assembly (right)

The light emitted from an erbium-doped fiber source (amplified spontaneous emission (ASE)) is sent to a first CFBG placed in the explosive *via* the port 2 of a 3-port circulator. The light reflected by the CFBG is then split by a 10-90 coupler. 10 % of the light signal is sent to an optical spectrometer while the remaining part (90 %) is sent to an InGaAs photodiode mounted in transimpedance amplifier (HCA-S FEMTO, 400 MHz, 5 V/mW) that provides a low impedance electrical signal recorded by a fast oscilloscope (*e.g.* 5 GS/s) triggered a few microseconds before the operation of the explosive. An optical attenuator adjusts the output voltage to 1 V before test.

The CFBGs were photo-written using a chirped phase mask over a length of 100 mm. The center wavelength is 1545 nm and the full width at half maximum (FWHM) is 15 nm.

3. Calibration of velocity measurements

A calibration procedure is necessary to establish a transfer function between the position of the shock front and the voltage signal recorded by the oscilloscope. Two processes have been studied.

The first method uses a polishing or a progressive cut by a razor blade (uncertainty ± 0.1 mm). It provides a direct measurement of both chirp and voltage-to-position functions. However, this process is destructive, time-consuming and costly. Moreover, since the transfer functions are obtained from a sacrificed grating, their reliability is also strongly dependent on the reproducibility of the photo-writing process.

The second calibration method is based on OFDR (*Optical Frequency-Domain Reflectometry*) and makes use of a Luna OBR4600 device. It has the advantages of being non-destructive, fast and accurate in space domain (0.01 mm) [4]. In return, the spatial uncertainty is conditioned by the uncertainty about the value of the effective index n_{eff} of the guided mode. In practice, the mean effective index partly depends on fiber type and manufacturing conditions and also on the photo-writing process itself. A comparison of chirp functions obtained from both methods enables to get a better estimation of n_{eff} in order to improve the spatial localization of the shockfront.

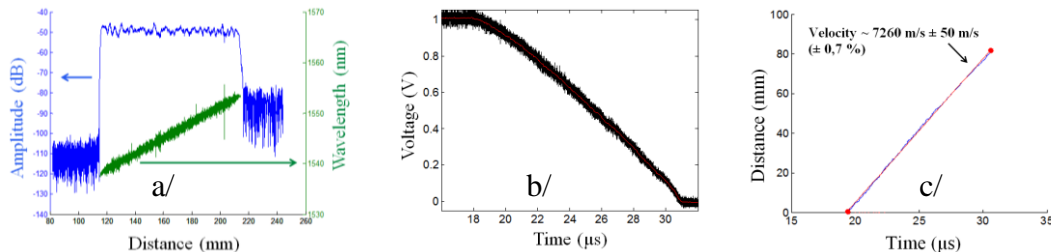


Fig. 2. a/ Example of chirp function obtained from OFDR measurements (Luna OBR 4600) providing wavelength-to-distance information b/ Typical signal obtained with the BraggFAST module and c/ estimation of the detonation velocity under sustained conditions over 100 mm.

The principle of the OFDR method is to record the spatial distribution of the light reflected back by the CFBG. As the laser frequency is linearly tuned, two interference signals (for each polarization) between the scattered light and a reference beam are recorded. The best spatial resolution ($< 10 \mu\text{m}$) is obtained for a tunable range over 85.4 nm. The sum of both signals provides the amplitude and phase of the backscatter in the spectral domain (irrespective of the polarization state), finally transposed in space domain (or time domain) by Fourier transform. In the particular case of a linear chirp, the amplitude profile $R(z)$ as a function of the distance z is identical to the reflection spectrum of the CFBG (taking into account the chirp factor). In addition, the derivation in the spatial domain of the phase argument $\arg(R(z))$ is related to the chirp [5]. The software provided by Luna automatically calculates this value (“phase derivative” procedure). The chirp is then deduced from the slope of this curve (Fig. 2a).

4. Experimental results

An example of a time signal is given in Fig. 2b. Its transcoding allows for the recovery of the evolution of the shock front position *vs* time. Detonation velocities in different parts of the explosive are then estimated by linear regression (least squares fit, Fig. 2c). Over short distance (< 10 mm), a statistical analysis shows the existence of a trade-off between spatial resolution and standard deviation on velocity (also observed with PDV). Over longer distances (*e.g.* 100 mm), the uncertainty in velocity is dominated by uncertainty about the group index, transcoding and shock sustainability. An experimental uncertainty of $\pm 0.7\%$ was observed (Fig. 2c) for a 100-mm long CFBG.

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