Embedded fiber-optic Bragg grating (FBG) detonation velocity sensor

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ABSTRACT

In order to fully calibrate hydrocodes and dynamic chemistry burn models, initiation models and detonation models of high explosives, the ability to continuously measure the detonation velocity within an explosive is required. Progress on an embedded velocity diagnostic using a 125 micron diameter optical fiber containing a chirped fiber Bragg grating is reported. As the chirped fiber Bragg grating is consumed by the moving detonation wave, the physical length of the unconsumed Bragg grating is monitored with a fast InGaAs photodiode. Experimental details of the associated equipment and data in the form of continuous detonation velocity records within PBX-9502 are presented. This small diameter fiber sensor has the potential to measure internal detonation velocities on the order of 10 mm/µsec along path lengths tens of millimeters long.

Keywords: Fiber gratings, high speed, velocity sensor, detonation, Bragg grating

1. Introduction

Chirped fiber-optic Bragg grating (CFBG) sensors in combination with relatively inexpensive commercial-off-the-shelf electronic instruments can be used to monitor high speed events and make measurements of detonation wave velocities inside of energetic materials such as high explosives and rocket propellants.

Initial fiber Bragg grating shock velocity measurement systems of this type were developed by Eric Udd at McDonnell Douglas and Blue Road Research and were used to support early testing of shock velocity tests conducted in water by exploding bridgewires (EBW) by Frank Roeske, Ed Roos and Jerry Benterou at Lawrence Livermore National Laboratory (LLNL) in 2004 [1].

The success of these early efforts by researchers at LLNL and Columbia Gorge Research enabled the prospect of a quantitative *in-situ* detonation velocity diagnostic. An *in-situ* detonation velocity sensor consists of a CFBG of known length, which is placed alongside or embedded directly within an explosive charge. Remote readout instrumentation, typically a fast photodiode, amplifier and an oscilloscope, can monitor the length of the CFBG as the detonation wave consumes the CFBG inside the explosive or energetic material. This embedded fiber approach has the unique potential to continuously monitor the detonation velocity inside new explosive compounds as well as to track the changes in detonation velocity as the detonation moves through the interfaces between different explosive compositions.

2. Chirped Fiber-optic Bragg grating velocity sensor: Principle of Operation

CFBGs have been used in the telecom industry for over a decade and are now readily available on the commercial market. Standard and customized CFBGs can be purchased from manufacturers with various physical lengths and optical characteristics. CFBGs reflect a narrow band of the optical spectrum while allowing light outside that band to pass through. (See figure 1) The manufacturer can customize the bandwidth $\Delta\lambda$, chirp rate $\boldsymbol{C}$, physical length, $\boldsymbol{x}$, as well as the reflectivity of these gratings. A key characteristic of CFBGs is that they can be customized to have a nearly

Fiber Optic Sensors and Applications VI, edited by Eric Udd, Henry H. Du, Anbo Wang, Proc. of SPIE Vol. 7316, 73160E
 · doi: 10.1117/12.819208

linear relationship between wavelength-integrated reflectivity vs. CFBG length. That relationship is the principle on which a CFBG detonation velocity sensor works.

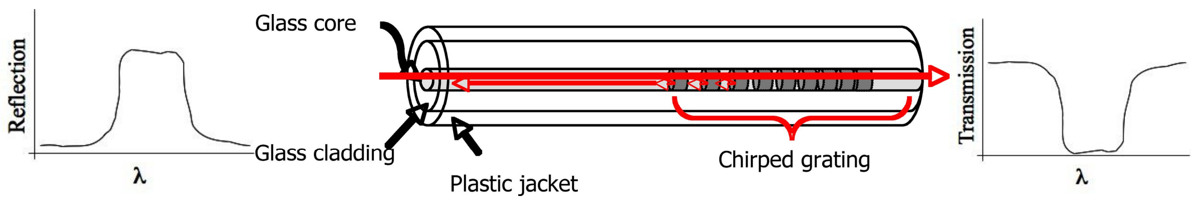

Figure 1 Chirped fiber-optic Bragg grating reflects a finite narrow band of light, while allowing out-of-band light to pass through.

In Figure 2 below, the reflection bandwidth of a CFBG was measured using an Ibsen I-Mon 400 spectrometer. A numerical integration of the reflectivity bandwidth is shown in blue. (For comparison, the dashed red line is a linear fit.)

Using the Bragg wavelength equation,

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

where $\boldsymbol{n}$ is the effective refractive index of the grating and Λ is the period of the grating. The approximate bandwidth of a chirped grating can be given as

$$grating\ bandwidth = \left|\lambda(x_{\max}) - \lambda(x_0)\right| = 2n_{eff}\left[\Lambda(x_{\max}) - \Lambda(x_0)\right] \tag{2}$$

where x_{max} and x_0 locate the physical ends of the grating[2]. A description of various methods used to locate the physical ends of the grating is in section 3 below.

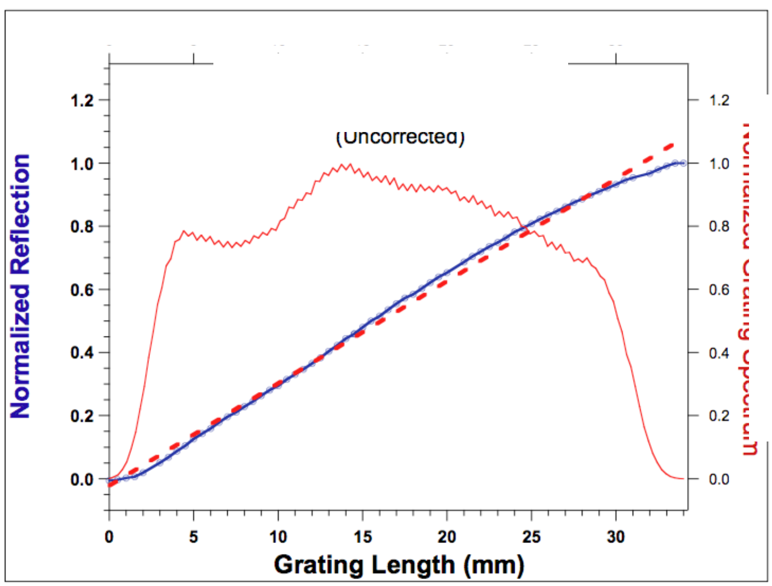

Figure 2 Typical CFBG reflectivity vs. physical length. The integral of the entire reflected bandwidth is proportional to the length of the CFBG. The dashed line is a linear fit of the reflection integral and is shown for comparison.

When the CFBG is illuminated by a broadband amplified stimulated emission (ASE) light source, the integrated reflectivity of the CFBG produces a reflected illumination intensity profile ***I***, which is proportional to the superposition of the ASE source intensity profile, ASE**(λ),** and the CFBG reflectivity profile, R**(λ),** over the grating bandwidth. This proportionality can be used as a transfer function to determine wavelength versus reflected intensity information.

We use an InGaAs photodetector to monitor the intensity of the ASE light reflected from the CFBG. As the fiber is destroyed by the detonation wave, the reflected light extinguishes. The signal voltage on the detector is proportional to the intensity of the reflected ASE light from the unconsumed CFBG at a given instant.

Since the detector's response is flat over the bandwidth of the CFBG, the normalized maximum voltage measured on the detector is

$$V_{\max} = 1 = \int_{\lambda_{-\infty}}^{\lambda_{+\infty}} ASE(\lambda)R(\lambda)d\lambda \tag{3}$$

This corresponds to the detector signal from an intact CFBG sensor prior to the start of the detonation process.

As the CFBG is destroyed by the detonation wave, a fraction of the returned light is lost, so that we measure,

$$V_{measured} = V_{\max} - \int_{\lambda_{-\infty}}^{\lambda^*} ASE(\lambda)R(\lambda)d\lambda \tag{4}$$

Solving this integral for λ^* for each instant in time and using the linear relationship of $x(\lambda)$ from figure 6, we find x as a function of time. Differentiation of this function gives the detonation velocity.

3. Measuring the physical length and location of fiber-optic Bragg gratings

In order to make effective use of a CFBG as an internal detonation velocity sensor, it is vital to know the *physical length* and the *location* of the CFBG in the fiber. Commercially produced CFBGs have *optical* characteristics (such as reflectivity bandwidth, chirp rate, total reflectivity and insertion loss) that are well-specified by the manufacturer. However, the *physical* characteristics of length and location are only generally specified because CFBGs are not commonly used as high-precision shock/detonation velocity sensors.

In our application, a method was needed to precisely determine the location and physical length of a CFBG in an optical fiber. Four methods were tried. The nearly identical CFBGs— FBG502 and FBG503 (from Redfern Optical Components Pty Ltd) were tested in each method.

1) A LUNA® optical backscatter reflectometer (OBR) was able to determine the physical location and length of a grating at the FWHM points to about 125 µm resolution. The CFBG length was measured to be 62.3 mm at the -3 dB points of the reflection spectrum and 72.5 mm long at the -20 dB points. (See figure 3)

2) We were able to make CFBG length measurements using a system that we developed which measures dispersion along the length of the fiber. The optical dispersion measurement agrees closely with the LUNA OBR measurement.

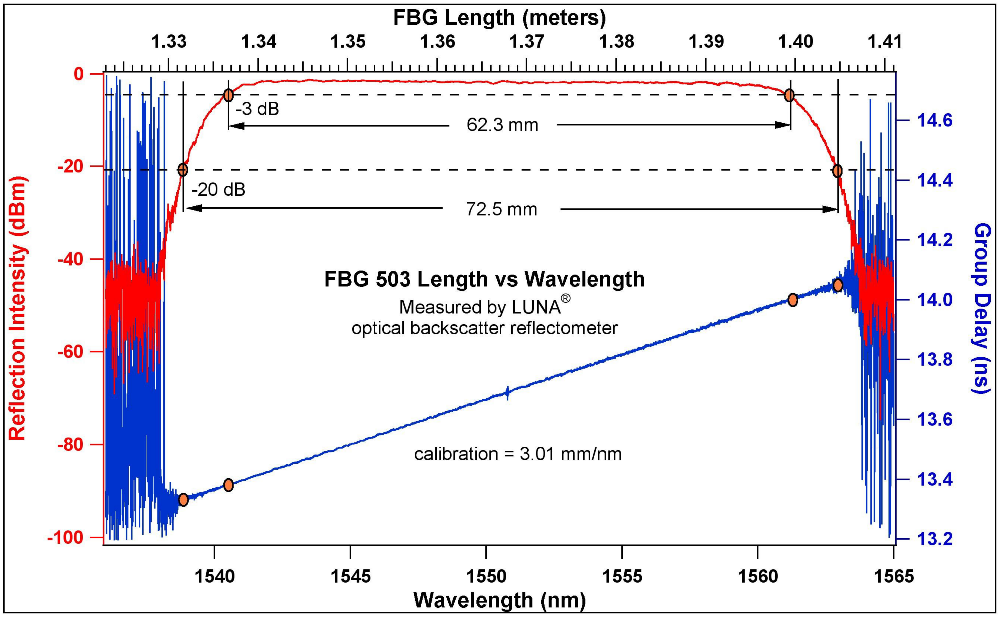

Figure 3 A LUNA® optical backscatter reflectometer was used to precisely measure the optical reflectivity vs. physical position in a 2 meter long 125 µm diameter SMF-28 optical fiber.

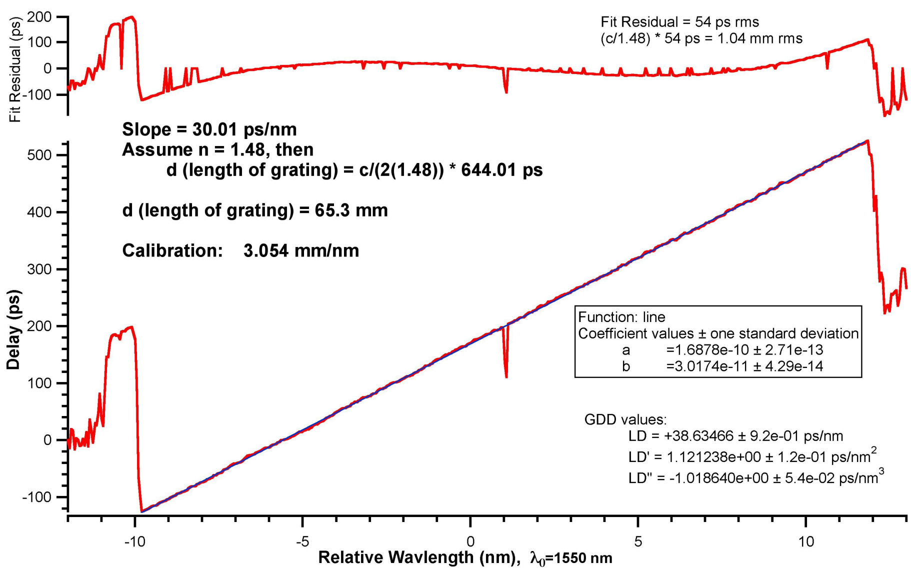

Figure 4 A LLNL fiber-optical dispersion test set was used to precisely measure the optical reflectivity vs. physical position of a CFBG in a 2 meter long 125 µm diameter SMF-28 optical fiber.

We found the FWHM of the physical length of CFBGs with an accuracy of about 50µm. However, it required several hours of scans to make these precise measurements. With the installation of a new laser in the optical dispersion measurement system, there is promise that higher resolution and higher scan speeds will be achieved.

3) We used a hot-tip micro-probe [3] (see figure 5) to locally heat the CFBG at selected locations along its length while observing the CFBG spectrum with a spectrometer (see figure 6). This method, improved by Garrett Cole, can be used to determine the length and location of the CFBG to about 250 μm resolution [4]. The hot-tip probe method creates local heating and causes a local red-shift of the reflected light at the exact position where the heated tip touches the grating. This local heating appears as a dimple in the CFBG spectrum. Using horizontal translation stage, it was relatively easy to create an accurate map of wavelength vs. physical length.

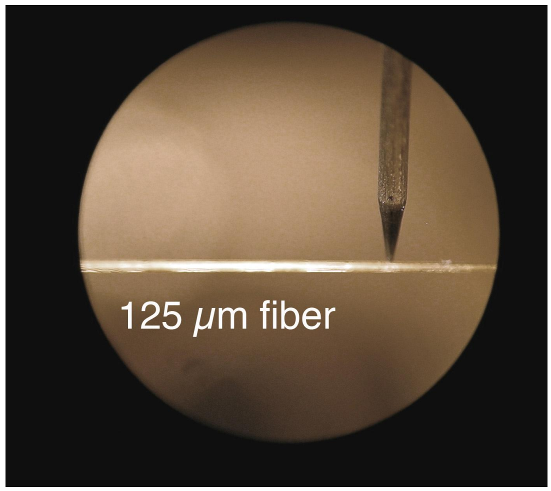

Figure 5 A tungsten probe, heated to 70°C is used to non-destructively measure the location and physical length of a fiber-optic Bragg grating. A high resolution translation stage was used to precisely position the hot-tip along the length of the fiber.

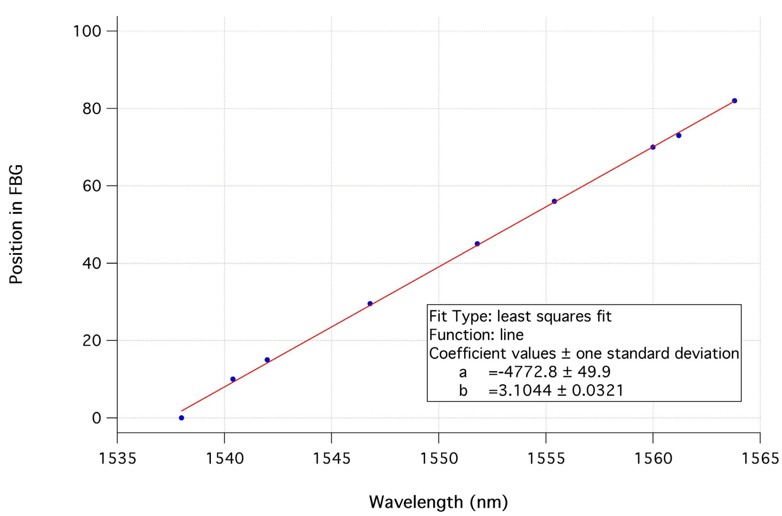

Figure 6 The hot-tip probe method of mapping CFBG wavelength to CFBG length revealed a chirp rate of approximately 3.1 ± 0.03 mm/nm.

The hot-tip probe method not only revealed the physical position of FWHM points, but also located the -50 dBm points of the CFBG spectrum, thus giving the physical length of the grating.

4) Using a femtosecond laser, which cuts very precisely with minimal heating damage adjacent to the ablation zone, we were able to map out the physical length and location of a "sacrificial" CFBG by laser-cutting the CFBG in 1 millimeter increments while observing the spectrum of the CFBG in real time. A proportional relationship between the bulk

reflection of a CFBG and its length was observed and measured during the cutting operation (see figure 8). This method revealed the end-to-end length of the CFBG down to -60 dB below the maximum intensity. Obviously, this was a destructive test, but it verified the physical length of the CFBG that was previously measured with methods 1, 2 and 3. This measurement agreed well with the prior 3 measurements.

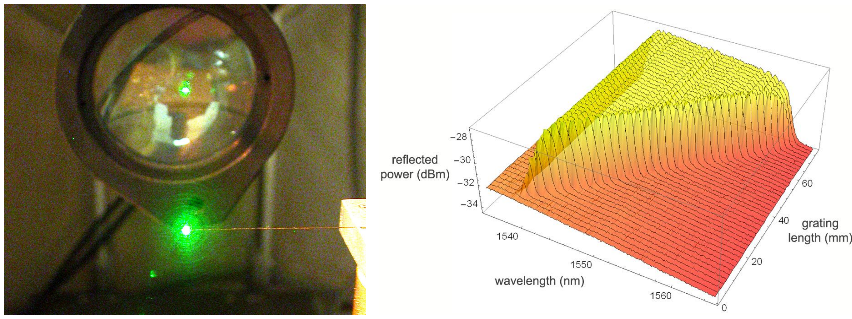

Figure 7 Femtosecond laser trims the CFBG (left). Data are recorded in 1 mm increments with 0.5 nm resolution during the experiment (right). From these results, the grating #502 is estimated to be 77 mm in length.

4. Internal detonation velocity measurement of PBX 9502

To test a prototype embedded CFBG detonation velocity sensor, an experiment was designed to measure the internal detonation velocity of a well-characterized explosive (PBX-9502). A CFBG was embedded inside a 4 inch long, 1 inch diameter column PBX-9502. The column was a stack of four 1 inch pellets of PBX-9502. A commercial RP-1 detonator driving a PBX-9407 booster initiated the column. Piezoelectric timing pins were placed along the 4 inch long column of PBX-9502 as a calibration reference (see figure 9). Instrumentation consisted of two oscilloscopes to record the pin timing marks, the fireset current viewing resistor (CVR) and the photodiode signal from the CFBG reflection. The CFBG was placed into a 1.6 mm outside diameter Teflon tube with a 175 µm inside diameter hole. The fiber/tube assembly was pushed through a 1.6 mm hole in the center of the PBX-9502 pellets.

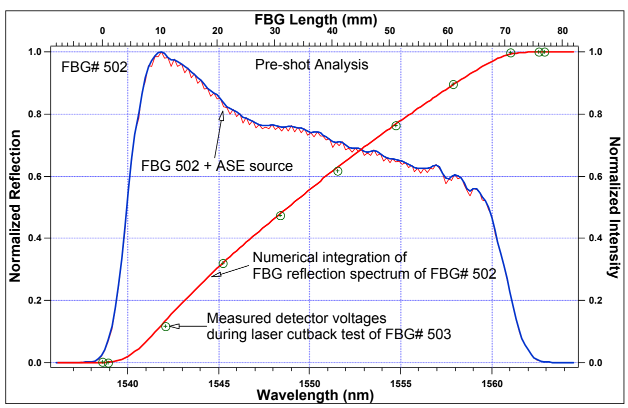

Figure 8 Pre-shot analysis of nearly identical FBGs #502 and #503. Both CFBGs were analyzed prior to the detonation experiment. FBG# 503 length was shortened in a laser cutback test. FBG# 502 length was shortened very rapidly in a detonation experiment. The numerical integration curve of FBG# 502 and photodiode output curve from FBG# 503 agree closely.

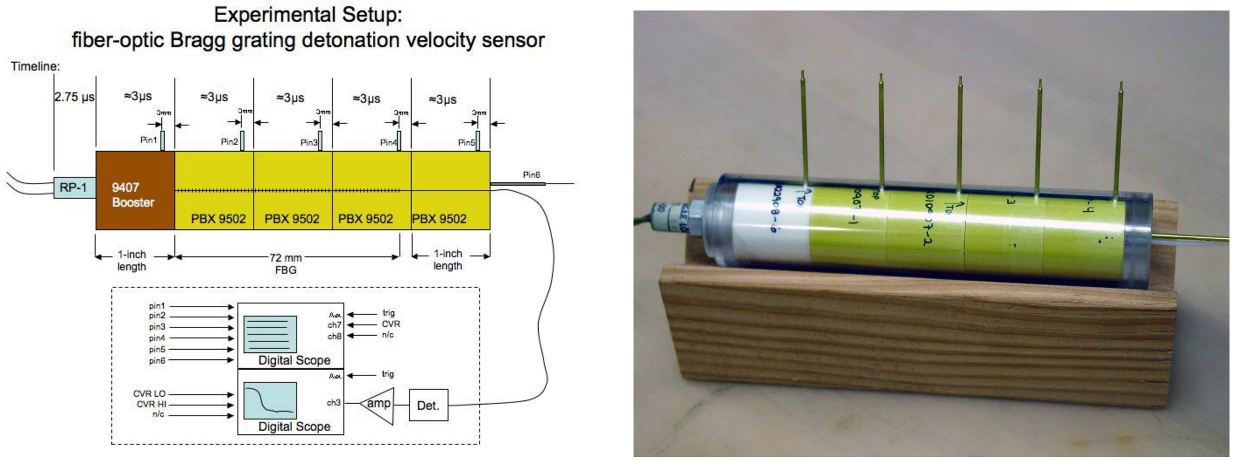

Figure 9 Experimental setup where a CFBG is embedded in a 4 inch column of PBX-9502 (left). The detonation was initiated with a commercial RP-1 detonator followed by a 1 inch PBX-9407 booster. Five piezo timing pins were placed at 1 inch intervals along the length of the PBX-9502 column (right).

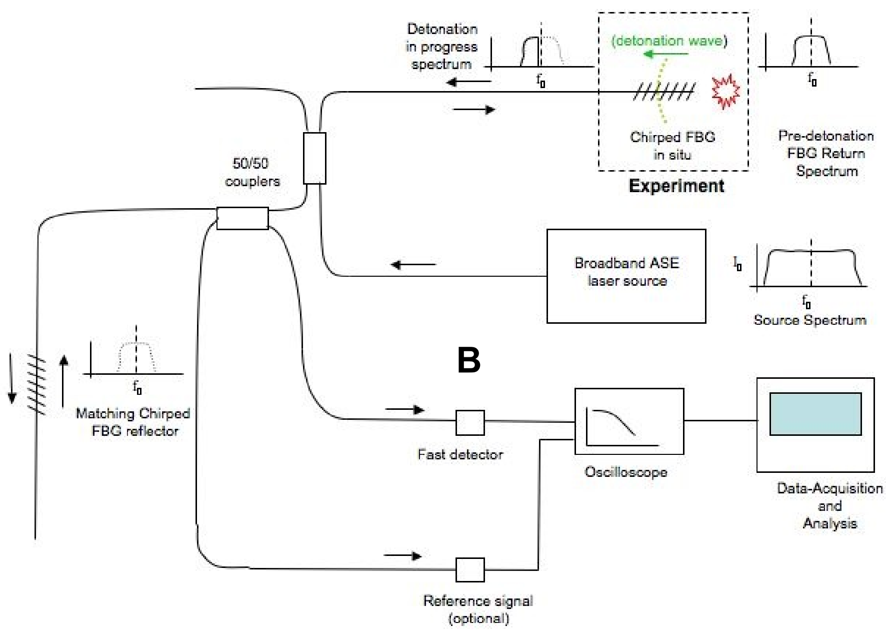

Figure 10 System block diagram of in-situ CFBG detonation velocity sensor.

The CFBG is illuminated by a broadband ASE source (see Figure 10). Light that matches the sensor CFBG's reflection bandwidth is returned. The rest of the ASE light outside the sensor bandwidth passes through the sensor CFBG and is dissipated in the explosive. The return signal is delivered by optical fiber to a photodiode, which produces a voltage proportional to the integral of the reflection bandwidth of the embedded CFBG and the ASE source illumination bandwidth.

The embedded CFGB sensor is destroyed as the detonation wave progresses through the explosive column, thus narrowing the reflection bandwidth of the grating. The photodiode signal is recorded on an oscilloscope during the detonation. A matching CFBG serves as a reference grating to eliminate any light from the detonation that is outside the bandwidth of the sensor grating (grating on the left of the block diagram in figure 10).

5. Analysis of results

The explosive assembly was test-fired in the 1kg containment tank at LLNL's High Explosives Application Facility (HEAF). Timing pin data and embedded CFBG data were recorded on two separate oscilloscopes, which were triggered from a common trigger source. The raw CFBG data is plotted with pin timing marks vs. time (see figure 11). The CFBG sensor data was expected to "bulge" out due to the shape of the integral of the reflection bandwidth (figure 8). Using the integral as a starting point, and assuming an expected detonation velocity of 7.7 mm/µsec, a numerical simulation of intensity vs. time was performed (see figure 12). There is very good agreement between the simulation and the raw sensor data. The experimental data diverges from the simulated data at the ends of the grating where one would expect lower sensitivity to changes in the grating length due to the curvature of the integral in that region.

Detector "A" sees the return signal coming directly from the CFBG embedded in the HE sample. Detector "B" sees the same return signal, but only after it has been reflected off a matching reference CFBG (left side of diagram). The purpose of the reference CFBG was to act as a narrow band pass filter which prevents out-of-band light from reaching detector "B". It turns out that both signals were identical and the reference CFBG is not needed to capture a good return signal from the detonating HE. Detector "B" is not needed because the CFBG and detector optical bandwidths are extremely narrow compared to the optical bandwidth of the detonation itself.

Using the mapping of grating length to reflection bandwidth (figure 8), it is possible to map the position of the detonation wave vs. time, thus giving a continuous time history of the position of a detonation velocity wave inside the high explosive (see figure 13).

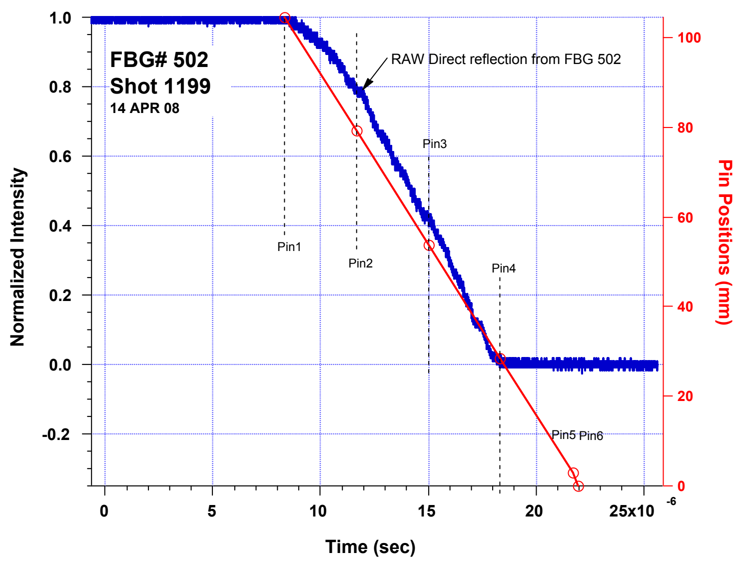

Figure 11 Raw data from test-firing PBX-9502. Raw pin data PBX-9502 average velocity is 7.65 mm/µsec. Raw CFBG sensor data had good signal-to-noise ratio compared to earlier test done in 2007.

6. Future sensor applications for embedded CFBG detonation velocity sensors

Improvements include establishing techniques using composite (chirped and non-chirped) FBG sensors that have well-defined edges would allow more accurate measurements of the physical length of the sensor. Improvements in the experimental design and analysis could help resolve the uncertainty of detonation velocity at the ends of the grating. Since embedded CFBG detonation velocity sensors measure the rate of the destruction of the CFBG inside shocked materials, these sensors potentially can measure the speed of propagating detonation waves that are off-axis from the optical fiber. CFBGs can be placed not only *inside* explosives, but also along boundaries between explosives and metals or other materials.

Additional improvements include developing techniques for drilling extremely small diameter holes in high explosives that would allow the insertion of CFBG sensors into the bulk high explosive. Based on the embedded fiber-optic sensor work done by Dave Hare[5] et al, we believe that a 125 µm diameter CFBG sensor will cause minimal perturbation to the detonation wave being measured. CFBG sensors can then be placed *inside* high explosives and propellants to measure with high accuracy, the detonation velocity and physical parameters associated with very high-speed events.

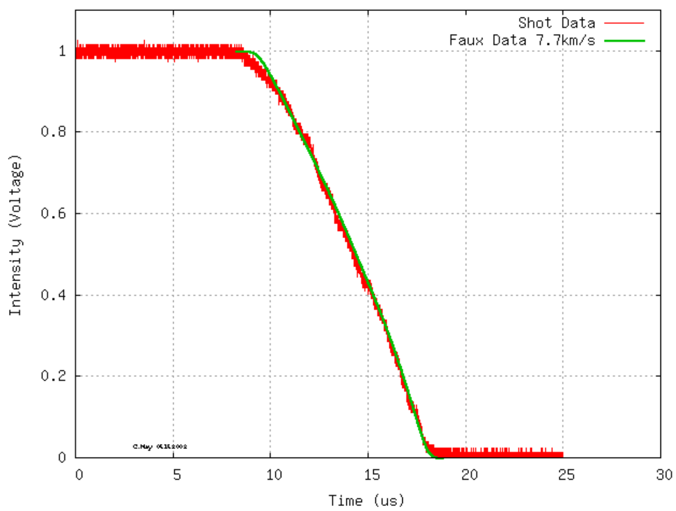

Figure 12 Raw data shows good correlation to numerical simulation of a constant velocity detonation.

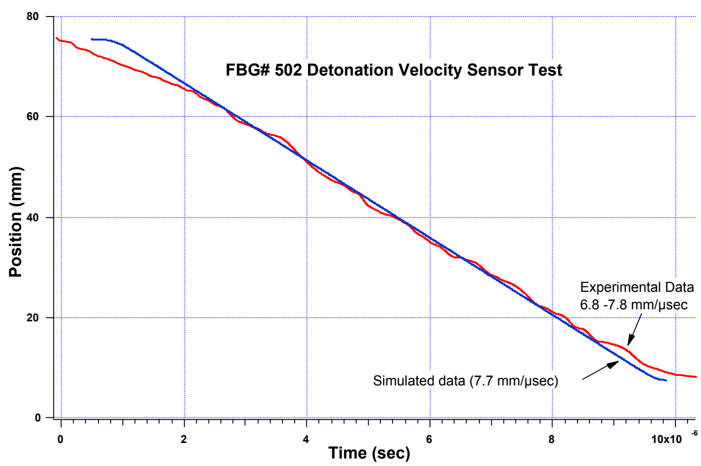

Figure 13 Final data analysis of embedded CFBG #502 velocity sensor. Experimental results agree with numerical simulation in the center portion of the grating.

Conclusions

A chirped FBG is an attractive candidate for further development as a detonation velocity diagnostic. The results displayed in figures 12 and 13 convincingly show that a strong, continuous-in-time signal can be obtained from a CFBG that is closely related to the detonation velocity. Although there are grating end-effects that we don't yet fully understand, our analysis obtains the correct detonation velocity in the central (highest fidelity) portion of the grating.

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.