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IN-SITU CONTINUOUS DETONATION VELOCITY MEASUREMENTS USING FIBER-OPTIC BRAGG GRATING SENSORS

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1 ABSTRACT

In order to fully calibrate hydrocodes and dynamic chemistry burn models, initiation and detonation research requires continuous measurement of low order detonation velocities as the detonation runs up to full order detonation for a given density and initiation pressure pulse. A novel detector of detonation velocity is presented using a 125 micron diameter optical fiber with an integral chirped fiber Bragg grating as an intrinsic sensor. This fiber is embedded in the explosive under study and interrogated during detonation as the fiber Bragg grating scatters light back along the fiber to a photodiode, producing a return signal dependant on the convolution integral of the grating reflection bandpass, the ASE intensity profile and the photodetector response curve. Detonation velocity is measured as the decrease in reflected light exiting the fiber as the grating is consumed when the detonation reaction zone proceeds along the fiber sensor axis. This small fiber probe causes minimal perturbation to the detonation wave and can measure detonation velocities along path lengths tens of millimeters long. Experimental details of the associated equipment and preliminary data in the form of continuous detonation velocity records within nitromethane and PBX-9502 are presented.

2 INTRODUCTION

Fiber Bragg grating sensors in combination with high speed read out units based on optical filters can be used to monitor high-speed events such as damage to composite panels and make measurements associated with detonation waves and interactions involving highly 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 bridegwires by Frank Roeske and Ed Roos at Lawrence Livermore using equipment supplied by Blue Road Research in 2004.

The success of these early efforts lead Jerry Benterou at Lawrence Livermore National Laboratory and Eric Udd of Columbia Gorge Research to expand and refine these early efforts to obtain more definitive results and enable the prospect of more complete and quantitative *in-situ* diagnostics to be embedded directly within an explosive charge.

Improvements include establishing techniques that enable chirped fiber Bragg grating (FBG) sensors to have well-defined edges allowing accurate measurements of the physical length of the sensor. Additional improvements include developing techniques for drilling extremely small diameter holes in high explosives which would allow the insertion of FBG sensors into the bulk high explosive which will cause minimal perturbation to the detonation wave being measured. FBG 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.

3 THEORY OF OPERATION

3.1 FIBEROPTIC BRAGG GRATING (FBG) SENSORS

Optical fiber that is used to support telecommunications and sensing applications consists of a light guiding region called the core of an optical fiber, which has higher index of refraction than the surrounding cladding. Typically, for low cost optical fiber, the primary component is very pure quartz with the light guiding core area being doped with small amounts of germanium. Normally these optical fibers are designed to have very low loss and back reflection. However, by using laser beams in the ultra-violet operating at approximately 240 nm, it is possible to alter the effective index of the core by changing the nature of the quartz (silicon dioxide) and germanium in the core area. Effectively, exposure to this short wavelength radiation increases the index of refraction locally. This effect can be used to write fiber gratings consisting of periodic variations of the index of refraction along the length of the fiber core. One procedure for accomplishing this is shown in Figure 1. Here two short wavelength laser beams are arranged so that they intersect at an angle, resulting in an interference pattern of bright and dark fringes that may be side imaged through the side of an optical fiber. The effective index along the length of the optical fiber is altered in a periodic manner through color center damage and generation of non-binding oxygen hole vacancies in the $Si0_2$ matrix. This refractive index change remains after the laser beams are removed and results in a periodic modulation of refractive index in the third decimal place. This procedure is much like exposing photographic film, where the “image” is a pattern written into the fiber core that persists after the laser light is removed.

It is possible, however, to make a chirped fiber grating where the period of the fiber grating and its index variations along the core are not uniform. This may be done by changing the angle of the intersecting laser beams along the length of the fiber grating or it may be accomplished by using a second type of fabrication process involving a phase mask. In this procedure, illustrated by Figure 2, a single laser beam is imaged through a quartz plate whose thickness varies by half a wave between successive sections. In this manner, an interference pattern is generated that may be side imaged to form a grating. After the fiber grating is written, it can be illuminated with a broadband light source such as a super-radiant or ASE (amplified stimulated emission) fiber light source. When the index change of the fiber core is periodic and uniform along a length on the order of 1 to 10 mm, the FBG returns a relatively narrow spectral peak called the Bragg wavelength (λ_B) as is shown in Figure 3.

For the case of fabricating a chirped fiber grating, the phase mask may have a period that is more closely spaced on one end than the other. This in turn, can be used to generate "chirped" fiber gratings whose period changes from closer to farther spacing along the length of the fiber. This procedure can be used to form a chirped fiber grating which reflects a broad spectrum from a spectrally broad band light source as is illustrated by Figure 4.

Because portions of the fiber grating may effectively spectrally "shade" successive regions, the reflection and transmission of a chirped fiber grating may vary and can be designed to be "flat" over the spectrum as in Figure 4. The reflection associated with an actual chirped fiber grating of 50 mm length is shown in Figure 5.

Figure 5 also illustrates the output spectrum of a typical ASE light source that has been "gain flattened" using an external fiber grating. The spectrum is relatively flat over the region centered about 1550 nm but exhibits significant variations in amplitude at wavelengths shorter than about 1540 nm. This is typical for this type of light source, which has the advantage of being very low noise while outputting high optical power levels. It is important to select an FBG whose reflection spectrum matches the relatively flat output region of the ASE light source.

3.2 MEASURING DETONATION VELOCITY USING CHIRPED FIBER GRATINGS

In the early stages of detonation, the behavior of any explosive during the dynamic transition from early low-order detonation up to the full-order detonation at nominal detonation velocity is critical in determining the robustness of the initiation and detonation process. This duration of transient detonation velocity change is commonly referred to as dynamic shock detonation and these transients scale to very short times and distances for ideal explosives. In the modern, non-ideal insensitive explosives used today, these transients scale to longer times and distances similar to the increase in failure diameters. Experimental techniques that measure a continuous change in detonation velocity provide insight into this dynamic regime of initiation physics. Continuous velocity measurements are significantly more accurate in determining this run-up in velocity relative to single point measurements (such as ionization pins or piezoelectric shock pins), which yield only the average velocity measurement between the individual pin placement points.

Figure 6 illustrates this principle. A 34 mm chirped fiber grating was physically cut using a femtosecond laser in 0.5 mm increments through its entire length, simulating the shortening of the FBG caused by the propagating detonation. By monitoring the changes in the spectral reflection band, the length of the chirped fiber grating may be determined continuously. This is the same thing one would expect to see when an FBG is being consumed by an advancing detonation wave.

4 IN-SITU DETONATION VELOCITY MEASUREMENT EXPERIMENTS

The overall layout of the test system is shown in Figure 7. Here a broad band ASE light source, which in this case is a gain flattened 1550 nm erbium fiber amplified stimulated emission light source pumped by a 980 nm laser diode is used to inject light into a 50/50 coupler which has one of its output fiber legs attached to a chirped fiber grating that is placed in a high explosive. When the detonation occurs, a portion of the chirped fiber grating is destroyed and the spectral reflectance decreases. The signal that is back reflected from the chirped fiber grating is directed into a second 50/50 coupler. One output leg of this second coupler is directed into a reference detector that monitors the changes in the spectral reflection directly. The second output fiber leg is directed into an optical fiber that contains a second chirped fiber grating that has a spectral reflection that overlays that of the chirped fiber grating that is placed in the high explosive. The reflection from this second chirped fiber grating is then directed back into the second 50/50 coupler and a portion of this reflection is then directed to a second detector used to monitor this reflected signal. Since the chirped fiber grating, used as the sensor, and the second chirped fiber grating, used as the reflector, overlay spectrally, light that is associated with the blast that is not in the spectral band of the chirped fiber grating sensor is filtered from the output detector. By comparing the reference and reflected signals on the detectors, light induced by the blast wave in the detection band can be monitored and subtracted from the overall signal.

To demonstrate the viability of this technique, we construct an apparatus to launch light into a sensor fiber with an embedded chirped FBG, then placed this sensor fiber in a series of explosive volumes and recoded the integrated decrease in light from the chirped fiber Bragg grating (FBG) as it was destroyed. Two detonation run-up experiments were conducted at the High Explosive Applications Facility at LLNL in June 2007 using Nitromethane as the sample liquid explosive in one experiment and pressed pellets of PBX-9502 a modern insensitive explosive, in the other.

4.1 MEASUREMENT OF DETONATION VELOCITY INSIDE NITROMETHANE

The first test detonation involved placement of an optical fiber with a chirped FBG with a length of approximately 36 mm into a cylindrical container of nitromethane as shown in Figure 8. One end of the chirped fiber grating was placed at the bottom of the cylinder adjacent to a booster explosive (Comp-B).

The test results from the first test shot are shown in Figure 9. Both the reference and reflected signal detectors associated with Figure 8 show the chirped fiber grating being destroyed at the same rate. This would indicate that the light associated with the nitromethane blast is not affecting the output reference signal in a significant way. The manufacturer of the chirped fiber grating was originally targeting an overall physical length of 50 mm. However when laser cut back tests were performed on a second identical “50 mm” chirped FBG, the spectrum did not change until it was cut back to approximately 14 mm. This indicates that the length associated with the spectral band of the cut back fiber grating spectrum associated chirped fiber grating #509 was about 35 or 36 mm. Using this experimentally derived shorter length, the velocity matches up very well with the velocity associated with the pin timing used to support the first detonation test.

This unexpected result (i.e., discovering that the physical length of the FBG was not the same as the manufacturer’s specification) emphasizes a key principle. In order to derive an accurate detonation velocity measurement, one needs to first know the true physical length of the FBG.

4.2 MEASUREMENT OF DETONATION VELOCITY INSIDE PBX-9502

The second test set was supported using a cylinder packed with four 25.4 mm diameter PBX-9502 pellets 25.4 mm long. The effective spectral “length” of the second “100 mm” chirped fiber grating was approximately 62 mm in length (measured by laser cut back testing of a similar “100 mm” FBG). The 62 mm fiber grating was inserted into the center of cylinder filled with PBX-9502 pellets as illustrated by Figure 10. The edge of one side of the 62 mm chirped fiber grating was placed near the Comp-B booster and provided coverage through nearly three sections of pellets during the second blast event.

Figure 11 shows the test results for the second shot that was conducted in a larger test tank. The results appear similar to the first test although there is additional noise associated with the last third of the slope associated with the destruction of the chirped fiber grating. This may be due to electrical pickup by the circuitry associated with the optical detectors. If this is the case, better shielding and isolation could be applied to eliminate this noise source. An electrical transient on the optical detector waveform is seen and correlates to the high-current capacitor discharge unit firing and bursting the bridgewire in the RP-1 detonator.

Also, the addition of a fast trans-impedance amplifier stage after the detector stage would boost the current signal well above the baseline noise of the digitizing oscilloscope. Since the fiber grating sensor system is electrically isolated except the electro-optic component circuitry in the control room (light source driver and detector support circuits), the prospects of reducing this source of noise is very good.

4.3 DETERMINATION OF THE PRECISION OF VELOCITY MEASUREMENTS

During the course of performing these tests, it became evident that the chirped FBG specified at 100 mm actually had a physical length of approximately 62 mm. This was determined by using two sets of gratings on a physical cut-back test on the 100-mm and 50-mm chirped fiber gratings. This was done by laying out the fiber gratings in a straight line and then physically cutting them back with a femtosecond laser by increments of 0.5 mm of fiber until the spectral band of the chirped fiber grating changed in a measurable manner. The spectrometer used to support these tests was an Ibsen I-MON 400 that can be operated at a sample bandwidth of 200 Hz over the 1520 to 1580 nm spectral band. This spatial calibration was very useful in providing real time feedback during the cut back tests.

4.4 ANALYSIS OF IN-SITU DETONATION VELOCITY MEASUREMENTS

Besides detonation experiments, several the fiber gratings as described above were cut back from the longer wavelength end until a clear transition in response was observed. This allowed an unambiguous starting point for the chirped fiber grating sensor position. Plotting the response via a cut back test also allowed the overall position and effective length of the chirped fiber grating to be established. For example, a so-called “50 mm” FBG was laser-trimmed at 0.5 mm increments along its entire reflection band pass shown in figure 12 and figure 13. It was quickly discovered that the true physical length of the FGB was 34 mm, not 50 mm as specified by the manufacturer.

The cut back method, via mechanical or laser trimming can be used to establish the exact position of the fiber grating ends in terms of significant spectral bandwidth change. This method of finding the absolute physical length of an FBG also produced a transfer function of FBG length vs. reflection as seen in figure 6.

There is very good agreement between the raw data from the laser cutback test, and a numerical integration of the 34 mm FBG reflection bandwidth (see figure 14). This implies a procedure in which the physical length of the FBG is measured and the optical reflection bandwidth is recorded prior to the detonation. Knowing the physical length and the reflection bandwidth of the FBG sensor allows for analysis of the oscilloscope data to derive the length vs. time history of the detonation. Next, the velocity of detonation can be calculated by simply taking the derivative of the FBG length vs. time data. Since the data recorded is on an oscilloscope, this continuous measurement can yield a continuous record of the detonation velocity inside the explosive being studied.

5 FUTURE OULOOK

5.1 IMPROVING DETONATION VELOCITY MEASUREMENT ACCURACY

Since it is essential to know the absolute physical length of the FBG and its location inside the high explosive or propellant *before* detonation, a reliable method to pre-measure the FBG length must be developed. Dispersion measurements using a tunable diode laser can be used to resolve FBG lengths to 300 microns. Therefore, knowing the FBG length to this accuracy promises that 50 mm FBG velocity measurements could be accurate to less than 1%. Also, the ASE source amplitude variations can be cancelled by dividing the raw oscilloscope signal by the normalized transfer function.

By exposing light of a greater bandwidth than the chirped fiber Bragg grating down the fiber through a circulator (or 2x2 coupler), the integral of the light reflected back under the bandwidth of the chirped fiber Bragg grating is the total light coming back from the circulator into a detector. Using a high-speed InGaAs/PIN photodetector and assuming a relatively flat-topped chirped passband for reflection and a spectrally flat light source, a linear reduction of reflected light back to the detector indicates that the shock wave is linearly destroying the chirped fiber Bragg grating. This optical signal reduction measures the integrated progress of the destruction of the printed grating by the detonation shock front.

Accurate measurement of the FBG length and accurate FBG placement will result in improved velocity and position information. The prospect of further improvements in this diagnostic to yield reliable, accurate and repeatable in-situ detonation velocity measurements is quite achievable.

5.2 APPLICATIONS OF IN-SITU DETONATION VELOCITY SENSORS

5.2.1 Run-to-detonation studies

There have been two types of metrology techniques, which continuously measure the detonation velocity of an explosive in the run-up to full order detonation. The first is an older technique based on microwave interferometry where a cavity is set up in a microwave waveguide filled with the explosive and interference from the reflection off of the plasma created at the detonation wave front forms a beat signal with the reference beam to continuously measure the detonation velocity acceleration. Limitations are the relatively small return signal, the large waveguide (and larger explosive sample) needed, and the conformance to a relatively linear waveguide detonation velocity measurement. The velocity also needs to be de-convoluted from the beat frequency of the microwave interference fringes from the detonation. A newer, more recently developed technique involves embedding plastic liquid-filled optical fibers within in a explosive volume where velocity is measured directly as Doppler shifted light that has been reflected off the shock generated refractive index jump at the shock wavefront within a liquid inside a section of Teflon tubing. As this technique uses current Fabry-Perot technology to measure the Doppler shift of the light, it provides a continuous measurement rather than a series of average velocities between measurement pins. This paper is derived from work originally performed using liquid light guides filled with a material which exhibits a significant jump in refractive index for a jump in pressure at the shock wavefront and applies it in a new direction using very much smaller telecommunication grade optical fibers. The advantage of telecom grade fiber is a very small diameter (125 microns typically, with a polyimide coating of 5 to 10 microns for protections) that has a minimal effect on the detonation behavior of non-ideal explosives with large failure diameters. Rather than look at the apparent Doppler shifted light reflected at the interface of the shock front – we literally print a chirped refractive index grating (commonly referred as a fiber Bragg grating) within a linear section of the fiber using a long exposure of ultraviolet radiation through a phase mask to make the fiber selectively reflect back light over a specified passband from an extended fiber optic light source specified to extend over the defined passband of the fiber Bragg grating. Because the grating is printed onto the physical fiber core, as the fiber is destroyed, the reflected light disappears, reducing the signal from the photodetector. The total light measured by a photodetector is a convolution integral of the spectral reflection function of the fiber Bragg grating, the spectral emission function of the l.55 micron light source, and the spectral response function of the photodetector.

5.3 DRILLING SMALL HOLES IN ENERGETIC MATERIALS

In order to accurately measure the in-situ continuous detonation velocity, the FBG sensor must be physically inserted into the high explosive or propellant and the sensor location must be well known with respect to the surrounding energetic material. This requires the development of methods to safely and inexpensively make small diameter holes in the energetic materials. One approach is to use a femtosecond laser beam to drill 100 to 200 microns diameter holes of medium depth up to 8 mm deep. The femtosecond laser drilling is performed inside an explosive containment tank and is controlled remotely by the operator. For deeper holes of depths from 10 to 100s of millimeters deep, rotating drill bits can be used, provided that safety considerations (friction, heat, shock, pressure) are taken into account. For example, machining and hole drilling of high explosives at Lawrence Livermore National Laboratory is done routinely as a remote-controlled operation inside explosive containment tanks.

6 FIGURES AND PICTURES

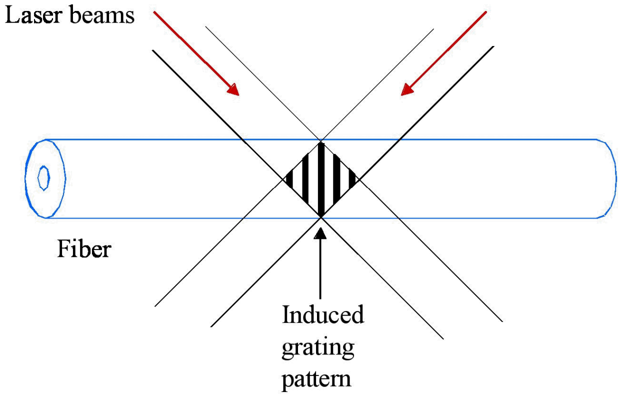


Figure 1.
Two coherent UV laser beams are overlapped onto the core of a single-mode fiber. The interference fringe spacing can be adjusted by the angle of incidence.

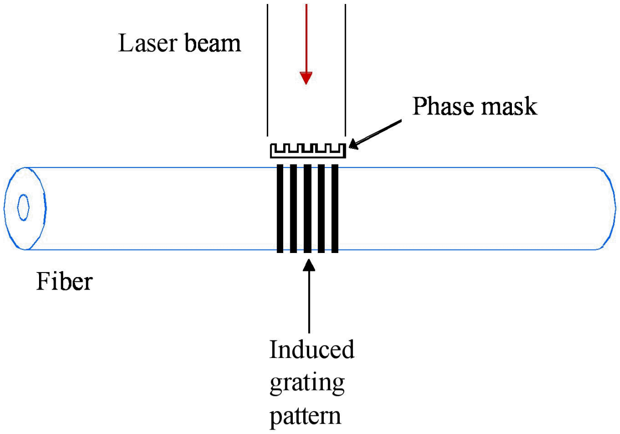


Figure 2.
A phase mask is used to write a "chirped" fiber-optic Bragg grating onto the core of a single-mode fiber.

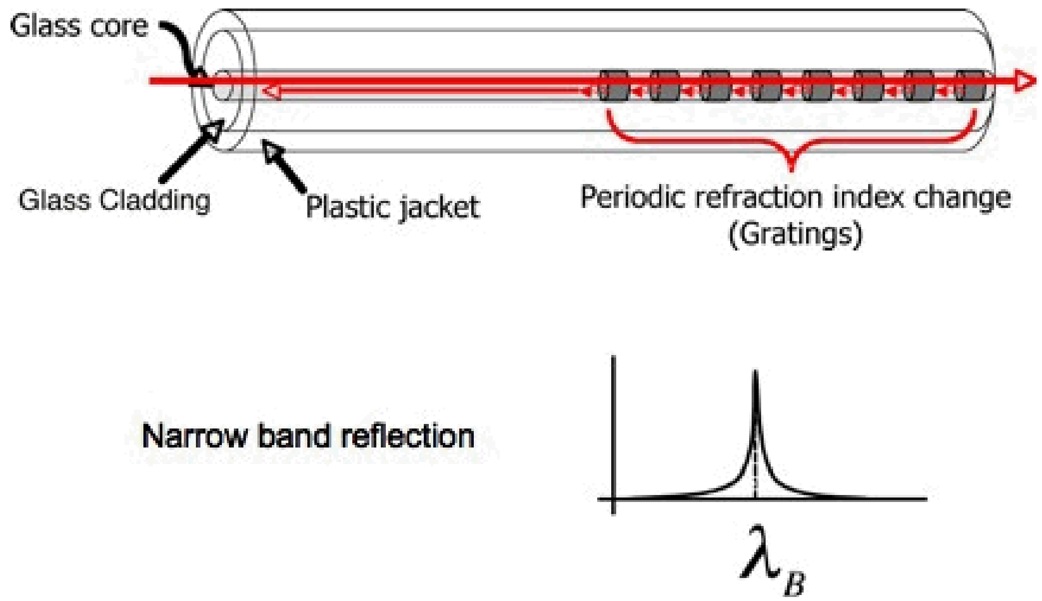


Figure 3.
This is a schematic of a constant pitch FBG where the grating pitch is held constant along the entire length of the grating. The reflection spectrum is defined by the Bragg condition $\lambda_B = 2n\wedge$, where $\wedge$ is the grating pitch.

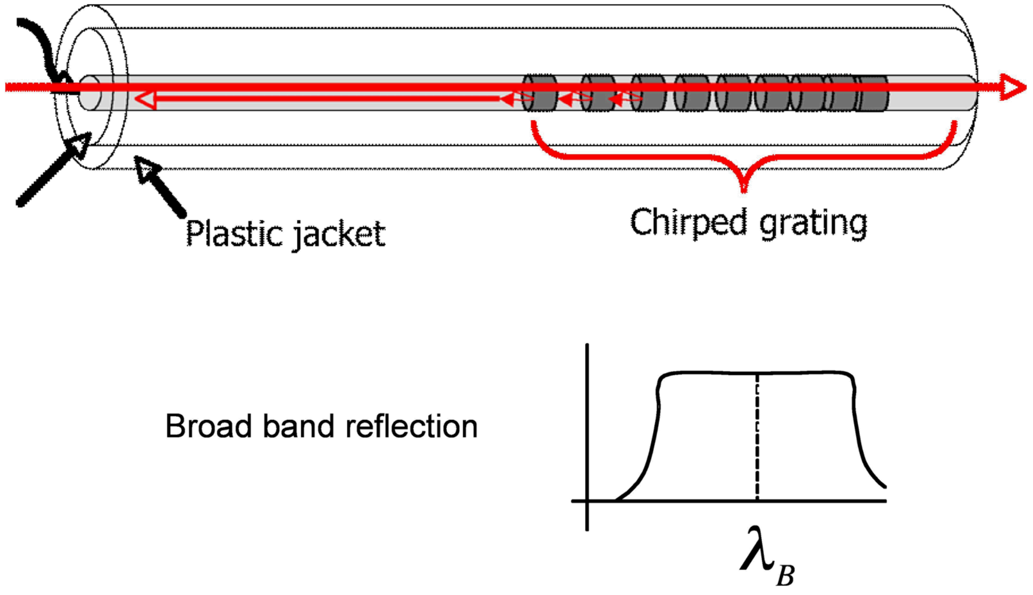


Figure 4.
This is a schematic of a chirped FBG where the grating pitch changes along the length of the entire grating. The reflection spectrum is a band of wavelengths where the Bragg condition exists for the range of different grating pitches.

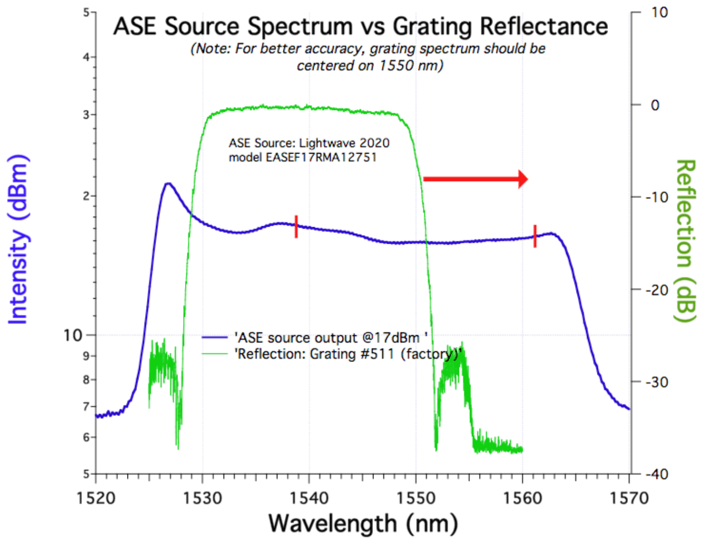


Figure 5.
The chirped grating reflection is flat-topped while the ASE source, which illuminates it, has much variation in its amplitude. Ideally, the FBG should be centered at 1550 nm to match the relatively flat region between the red marks.

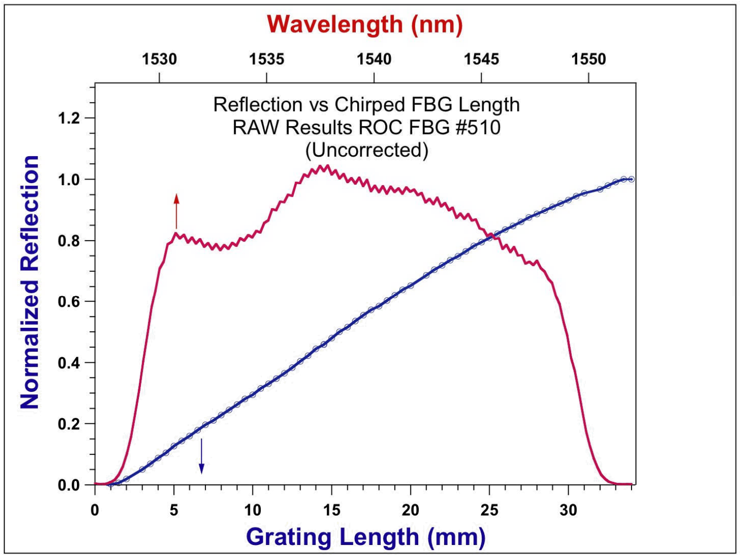


Figure 6.
Spectrum and bulk reflection of a 34 mm chirped FBG that was laser-cut using a femtosecond laser. The “bumps” on the FBG spectrum come from the amplitude variations of the ASE illumination.

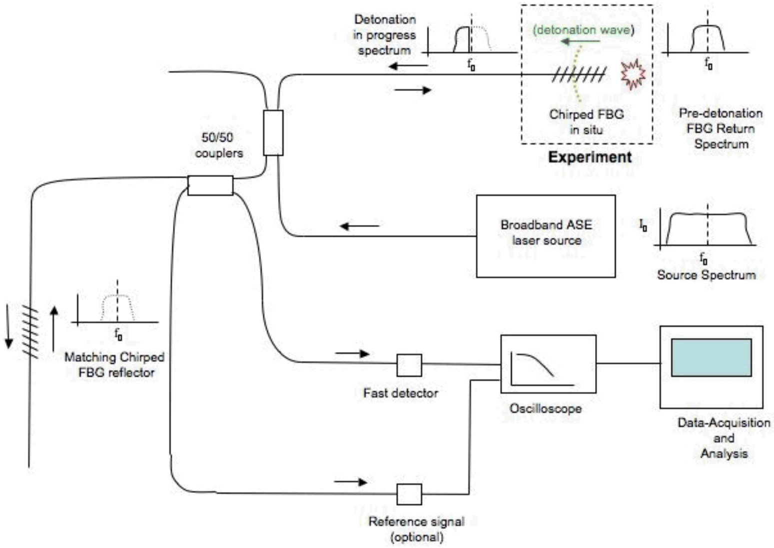


Figure 7.
Fiber Bragg grating detonation velocity sensor system block diagram.

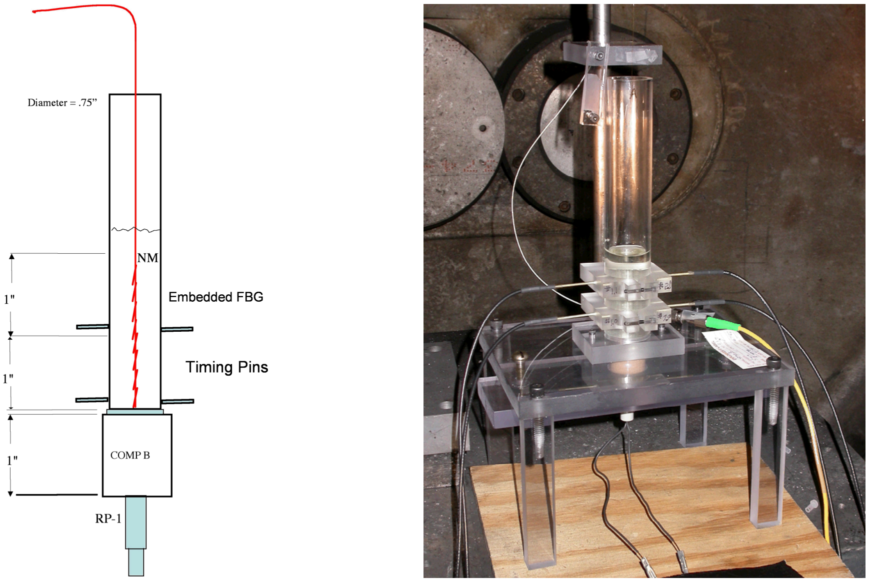


Figure 8.
Nitromethane detonation test configuration. A 36 mm FBG was embedded into the liquid nitromethane.

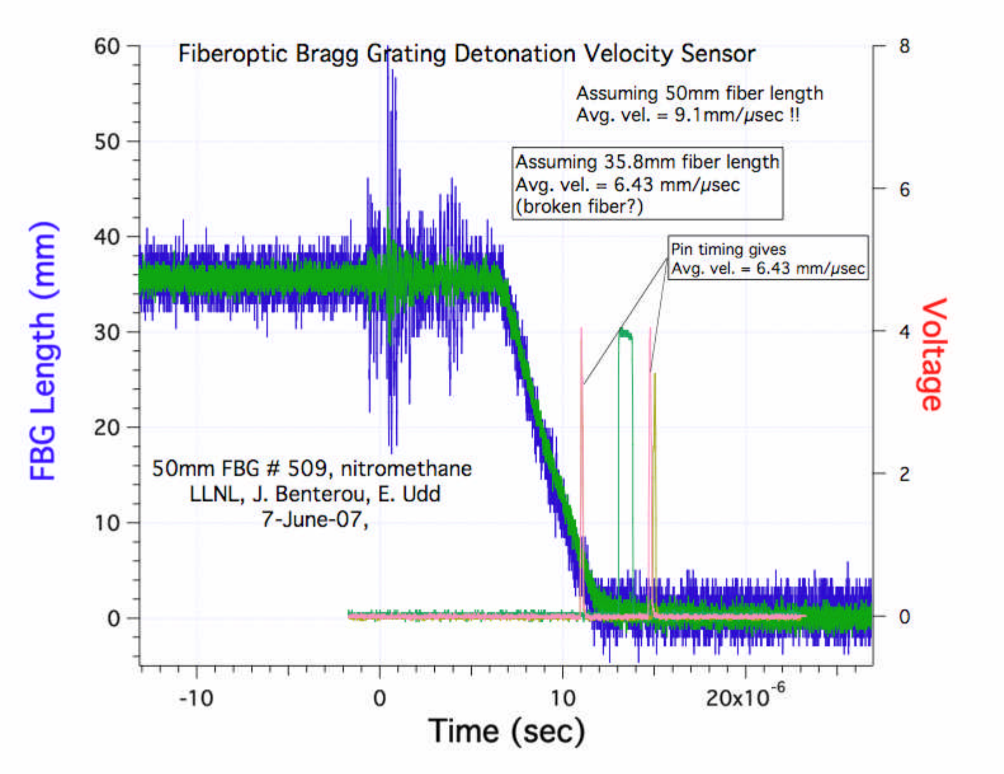
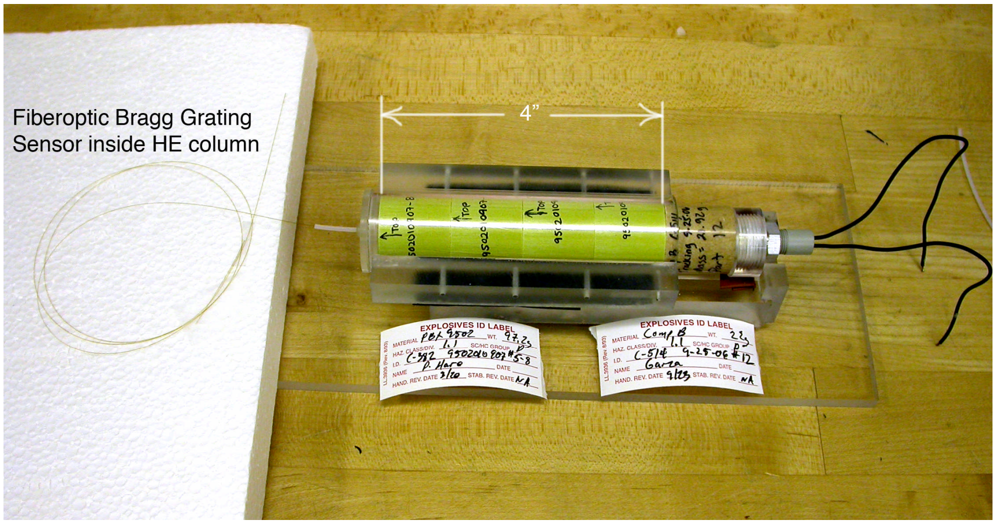


Figure 9.
In-situ velocity measurement of detonating nitromethane. Noise in signal comes from fireset EMP and low signal level from detectors.



EXPLOSIVES ID LABEL
MATERIAL PBX 9502 WT. 97.2g
HAZ. CLASS/DIV. 1.1 SC/HC GROUP D
I.D. C-382 950201007 #5-8
NAME P. Haro DATE
HAND. REV. DATE 3/20 STAB. REV. DATE NA
LL3936 (Rev. 8/93)

EXPLOSIVES ID LABEL
MATERIAL Comp B WT. 22g
HAZ. CLASS/DIV. 1.1 SC/HC GROUP D
I.D. C-514 9-25-06 #12
NAME Garza DATE
HAND. REV. DATE 9/23 STAB. REV. DATE NA
LL3936 (Rev. 8/93)

Figure 10.
Experimental setup for PBX-9502 in-situ velocity test. Fiber-optic Bragg grating sensor is embedded in the high explosive.

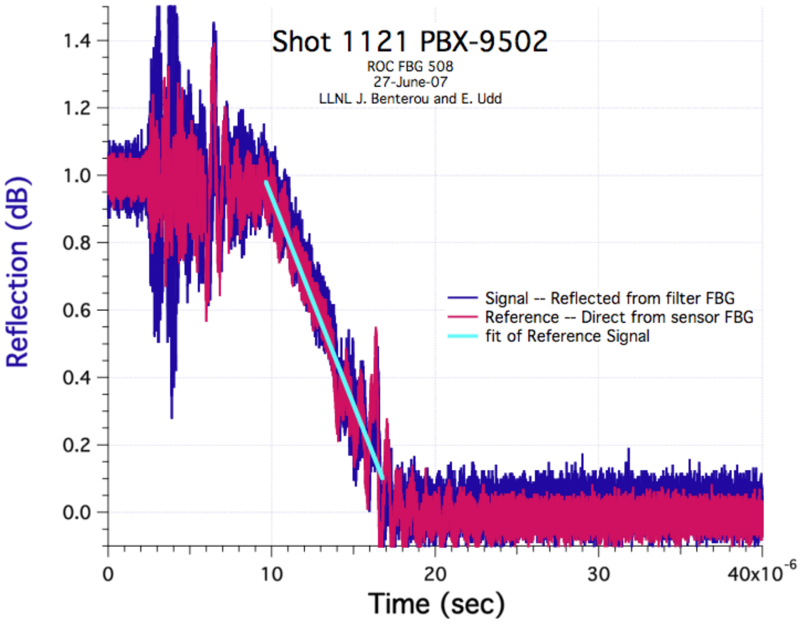


Figure 11.
Preliminary results of in-situ velocity measurement of detonating PBX-9502. Assuming the true physical length of the FBG is 62 mm, the velocity derived from this record is approximately 7.7 mm/microsecond.

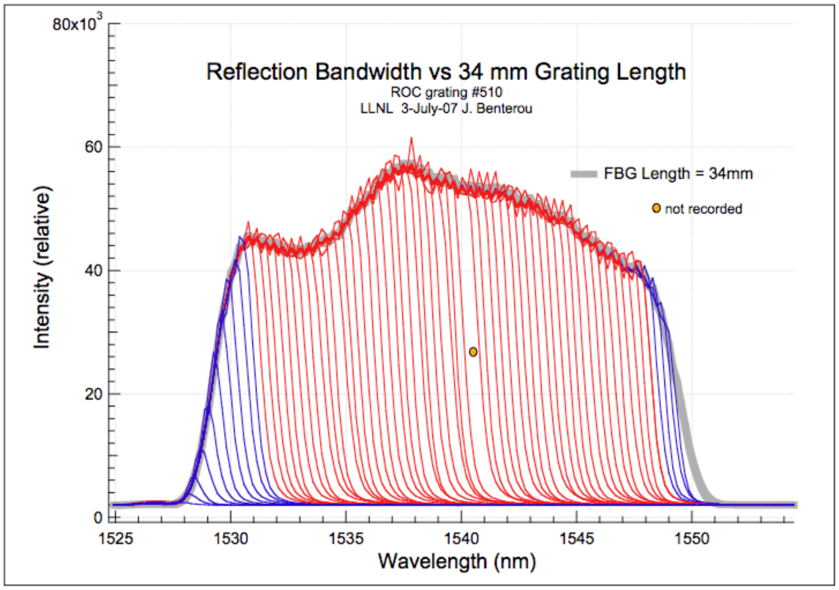


Figure 12.
Results of laser-cutting a fiber-optic Bragg grating sensor at 0.5 mm increments starting from the 1550 nm end.

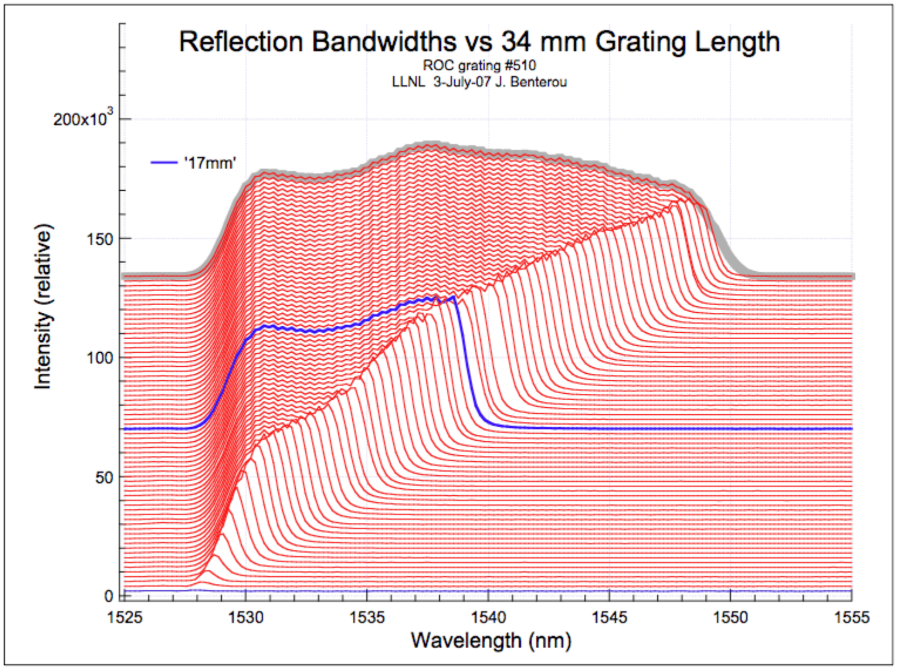


Figure 13.
Waterfall plot of grating spectra vs. FBG length.

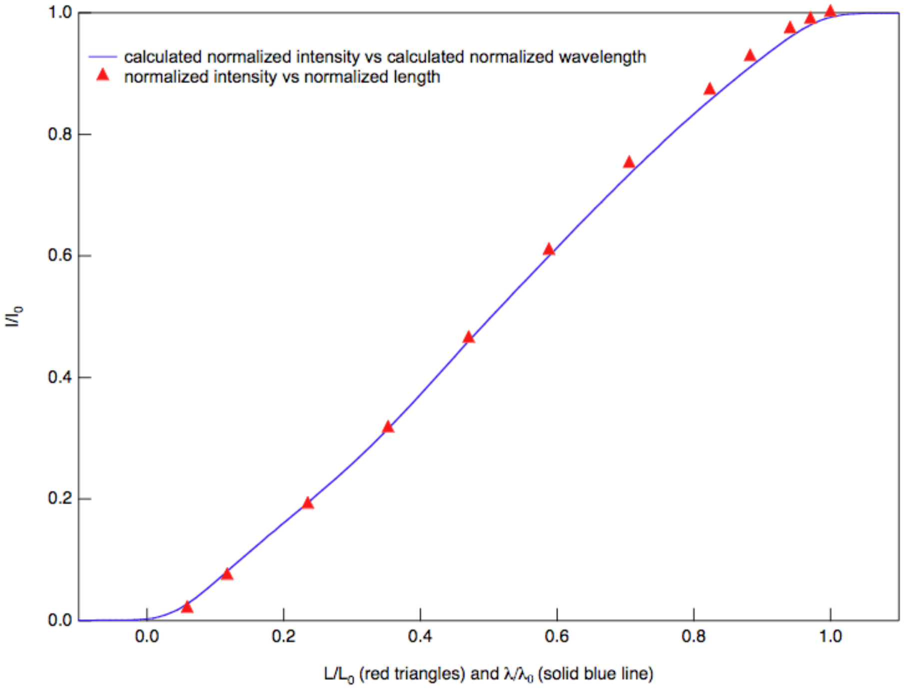


Figure 14.
Actual data from FBG reflection laser cut-back test shows good agreement with the numerical integration of the chirped FBG bandwidth.

7 ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank the following individuals whose hard work and dedication helped make this in-situ continuous detonation velocity sensor investigation successful:

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Steven Mudge	Mechanical design and fabrication of test fixtures
Jim van Lewen	Electronics instrumentation and data acquisition
Jay Dawson	Expertise in FBG instrumentation and measurements

8 LIST OF REFERENCES AND BIBLIOGRAPHIES

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