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Embedded optical probes for simultaneous pressure and temperature measurement of materials in extreme conditions

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Abstract. We present recent efforts at Los Alamos National Laboratory (LANL) to develop sensors for simultaneous, *in situ* pressure and temperature measurements under dynamic conditions by using an all-optical fiber-based approach. While similar tests have been done previously in deflagration-to-detonation tests (DDT), where pressure and temperature were measured to 82 kbar and 400ºC simultaneously, here we demonstrate the use of embedded fiber grating sensors to obtain high temporal resolution, *in situ* pressure measurements in inert materials. We present two experimental demonstrations of pressure measurements: (1) under precise shock loading from a gas-gun driven plate impact and (2) under high explosive driven shock in a water filled vessel. The system capitalizes on existing telecom components and fast transient digitizing recording technology. It operates as a relatively inexpensive embedded probe (single-mode 1550 nm fiber-based Bragg grating) that provides a continuous fast pressure record during shock and/or detonation. By applying well-controlled shock wave pressure profiles to these inert materials, we study the dynamic pressure response of embedded fiber Bragg gratings to extract pressure amplitude of the shock wave and compare our results with particle velocity wave profiles measured simultaneously.

1. Introduction

One of the outstanding issues in shock and detonation physics is the need for easy to field, high speed pressure and temperature diagnostics. While several techniques have succeeded in measuring shock pressures through particle velocity - such as embedded electromagnetic gauges [1] or laser velocimetry [2,3] – these techniques either require high magnetic fields or cannot penetrate optically opaque materials (VISAR, PDV, etc). What continues to be needed are embedded probes capable of in situ pressure and temperature recording with sub-μs response times. Fiber Bragg gratings (FBG) are an embedded and distributed reflectance sensor that for several years have been successfully fielded for measuring strain in structural monitoring applications [4]. Furthermore, FBG can provide fast measurement of detonation position and velocity monitoring [5,6]. As an extension of this work on detonation monitoring, Udd and colleagues demonstrated very recently that embedded FBG show high speed (sub-μs) response to dynamic pressure and temperature in deflagration to detonation tests (DDT) [7]. Peak dynamic pressures and temperature up to 82 kbar and 400ºC were measured. Also recently, we reported some initial pressure measurements in shocked inert samples [8]. Here, we focus on measurements where pressure effects dominate the dynamic FBG signal in an effort to study the pressure response of FBG and provide evidence of their usefulness in shock experiments.

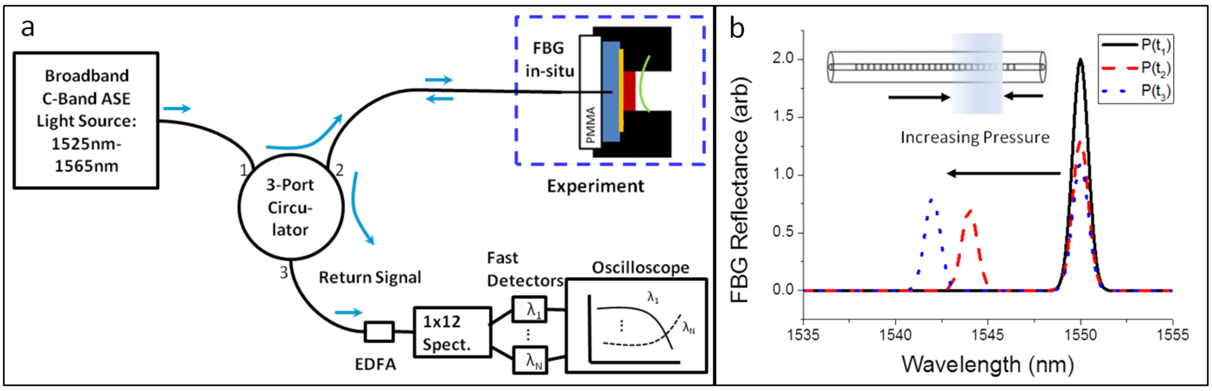

Figure 1. (a) Schematic of FBG pressure sensing system: light from a broadband light source is directed through a fiber circulator into a FBG reflector embedded in the experiment. The return light is directed through the circulator into the detection leg which includes a fiber amplifier (EDFA), spectrometer, detectors, and oscilloscope. (b) When the FBG is compressed due to the traversing shock wave, the FBG reflectance spectrum and return light is shifted to the blue.

The principle of operation for the FBG pressure/temperature sensor is shown in figure 1 and is similar to the system described in reference [6]. In figure 1(a), light from an incoherent broadband amplified spontaneous emission (ASE) source (1525 nm - 1565 nm) is launched into a single-mode 3-port fiber circulator. The circulator directs light to the embedded FBG sensor in the experiment. The highly reflective (~90%) narrowband (~2 nm) FBG reflects the light back through the circulator which is then amplified by an Erbium-doped fiber amplifier (EDFA). A bank of fast (125 MHz BW) InGaAs photodetectors and oscilloscopes record the shock wave and subsequent spectral shifts due to pressure and temperature. Various spectrally separating elements can be used between the EDFA and detectors such as a 1x12 fiber-coupled spectrometer (pictured) or fiber filters. FBG sensors have predictable thermal and mechanical response properties [7]. Previously, the wavelength shift of the returning light spectrum has been studied as a function of temperature and applied pressure [9,10]. Under applied pressure, the fiber reflectance spectrum shifts to shorter wavelengths, and in elevated temperature, the reflectance spectrum shifts to longer wavelength. Figure 1(b) shows a cartoon illustration of the FBG as it is compressed due to the propagating shockwave that causes the grating elements to compress thus shifting the reflectance band to shorter wavelengths.

2. Results

Two recent demonstrations of pressure measurements from FBGs embedded in dynamically loaded inert materials are shown. First, we show the dynamic response of a narrowband FBG centered at 1550 nm in shocked PMMA loaded by the single stage gas gun at LANL's Chamber 9. This demonstration was performed with a FBG written in side-hole fiber which has been shown to have a pressure only dependent peak splitting [7]. Simultaneous measurement of particle velocity was done with embedded electromagnetic gauge particle trackers as described elsewhere [1]. The second demonstration included a FBG written in traditional single mode fiber and placed in a water cell shocked by a high explosive charge. This experiment was performed at the Special Technologies Laboratory's (STL) boom box operated by NSTec in Santa Barbara, California. Laser velocimetry measurements were performed simultaneously on these water cell tests with VISAR (off the copper surface) and PDV (off the water/PMMA window surface).

2.1. Gas Gun Flier Plate Shocked PMMA

A total of five gas gun experiments with FBGs embedded in PMMA were conducted in 2013 at Chamber 9. Figure 2 shows the results from an experiment with peak pressures of 14.8 kbar as measured by the electromagnetic gauges. A 2 mm long side-hole FBG was embedded in a ~400 µm diameter hole drilled inside a cylindrical Poly(methyl methacrylate) (PMMA) sample (density 1.19 g/cm^3). The PMMA samples were approximately 1 inch tall and 2 inches in diameter. A 0.94 cm long stirrup gauge was affixed to the impact face of the PMMA target, providing the shock input condition. Also, a series of 9 electromagnetic particle velocity tracking gauges were embedded in the PMMA sample at a 30 degree angle so that ~0.8 mm separated the gauges in the direction of the shock similar to [1]. The particle velocity measured by these probes is shown in figure 2(b). The FBG was embedded at a location such that the shock arrival time coincided with shock arrival at gauge number 4. The PMMA target was impacted with a 57.2 mm diameter by 12.5 mm thick sapphire disk (z-cut) with a velocity of 0.414 ± 0.001 km/s. The single stage gas gun is a 72 mm diameter bore launch tube with a wrap-around breech that used helium as the working fluid. The spectral response of the ASE light source through the 1x12 spectrometer is shown in figure 2(c). Each spectral channel was recorded on a separate InGaAs detector and the pressure calibration of each channel (shown in the legend) is based on the side hole FBG response given in reference [7]. Figure 2(d) shows the dynamic

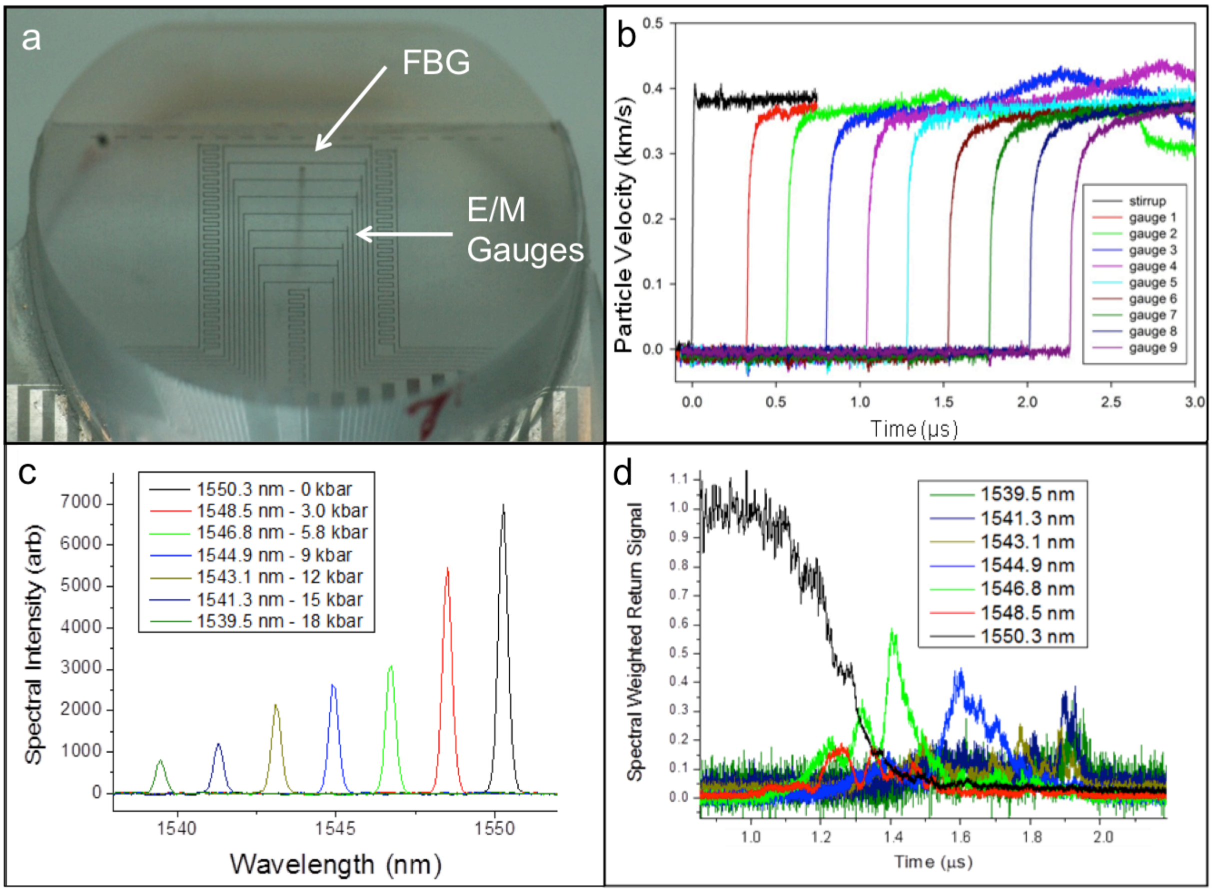

Figure 2. Dynamic pressure response of side hole FBG in gas gun driven PMMA target: (a) photograph of assembled PMMA target with embedded electromagnetic gauges for particle tracking [1] and FBG inserted from behind; (b) particle velocity measured with electromagnetic gauges that are separated by ~0.8 mm in the direction of the shock front; (c) spectral transmission through 1x12 spectrometer before the shot; (d) dynamic response of shocked side hole FBG in PMMA showing a maximum pressure shift of up to ~15 kbar (1541 nm).

spectral return signal with each channel renormalized for the relative transmission of the spectrometer (figure 2(c)). The maximum observed spectral shift is 9 nm (1541 nm bin) which corresponds to a pressure of ~ 15 kbar and compares well with the electromagnetic gauge measurements. We note that there is some evidence of disturbance in the gauge signals adjacent to the FBG (figure 2(b)). This was not observed in the other four experiments performed, and may have been from inadequate potting of the FBG into the PMMA.

2.2. HE Shocked Water Cell

A total of five gas gun experiments with FBGs embedded in PMMA were conducted in 2013 at Chamber 9. In July 2013 a series of eight explosively driven water cell ring-up tests were performed at STL in Santa Barbara. One of these tests is shown in figure 3. A 3.6 mm long FBG in traditional SMF28 fiber was placed into the water cell ~4 mm from the copper surface and parallel to the shock propagation direction. The shock was driven into the water cell through a 2 mm copper plate using an RP-1 detonator and a 25 mm diameter by 12 mm thick charge of PBX 9501 as shown in figure 3(a). Again, the spectral response of the dynamically pressurized FBG was first amplified by an EDFA, spectrally separated by the 1x12 channel spectrometer (see figure 3(b)), and detected using a bank of InGaAs detectors. Laser velocimetry was used to measure the velocity of the copper/water interface

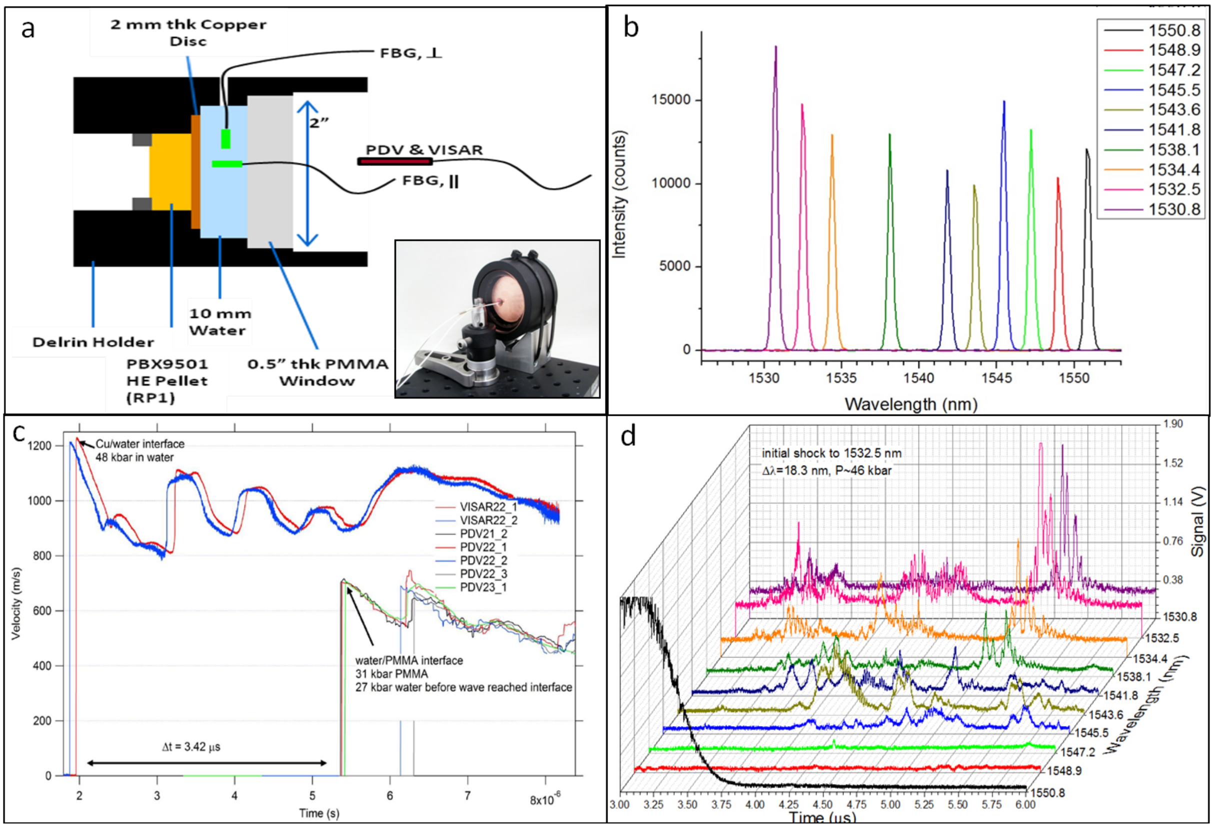

Figure 3. Experimental setup and data from explosively driven shock in water cell at STL: (a) side-view illustration showing target cell – a RP-1 detonator (not shown) drives a PBX9501 charge (25 mm diameter by 12 mm thick) into a copper plate that shocks a water target capped by a PMMA window; (inset) picture of the experimental target showing FBG inserted through the PMMA window into the water cell and PDV fiber; (b) transmission spectra of light source through 1x12 channel spectrometer; (c) compiled laser velocity traces for water cell experiments from VISAR on the copper/water interface and PDV on water/PMMA interface showing a peak pressure of 48 kbar; (d) Dynamic spectra measured by method in figure 1(a) showing initial spectral shifts to 1532 nm (corresponding to 46 kbar).

(VISAR) and water/PMMA interface (PDV) as shown in figure 3(c). In this shot, the maximum pressure of the shock wave in the water as given by the peak velocity in the VISAR trace is estimated to be 48 kbar. The dynamic spectral response of the FBG is shown in figure 3(d). The maximum initial pressure shift is 18.3 nm which according to the calibration of pressurized FBG in reference [7] corresponds to a pressure of ~ 46 kbar.

These two examples show good agreement between the pressures derived from the FBG response and traditional diagnostics (electromagnetic gauges or laser velocimetry). However, the time response of the fiber sensor and system is complex and not completely understood yet. In the gas gun shocked PMMA, we see a peak pressure of ~15 kbar from the FBG in comparison with the 14.8 kbar derived from the electromagnetic gauge particle velocity trackers. For the water cell ring-up demonstration, the peak pressure at the copper/water interface as given by VISAR is 48 kbar and the FBG shift corresponds to a pressure of ~46 kbar. We also note in the water cell ring-up data the periodic pressure increase with ~750 ns period (possibly due to copper spall reshocking the water) is evident in both the VISAR and FBG data very clearly. Also, in the FBG data in figure 3(d), we notice the periodic shifting between lower and higher wavelengths which also seems to track the inferred pressure oscillations in the VISAR velocity data. Finally, we should note that calibration between FBG spectral shift and pressure is based on the hyperbaric chamber calibration tests of Udd (reprinted in reference [7]) that was performed only up to static pressures of 1 kbar and on different types of fiber that those used in these experiments. Therefore, it is imperative that more thorough calibration of dynamic FBG pressure response should be performed and efforts are currently underway to do this. Furthermore, efforts to model the pressure in the water cell with CTH and to model the FBG dynamic spectral response are currently underway.

3. Conclusions

In this paper, we have provided two experimental demonstrations of FBGs as embedded sensors for measuring the important state variables of materials under dynamic extremes. While these efforts have focused on providing a proof-of-principle demonstration for determining the pressure response of the FBG, there is great hope that these sensors will also provide high-speed dynamic temperature measurements via *in situ* monitoring. Further work needs to be done on the exact calibration of pressure and temperature dependent FBG spectral shifts and efforts are underway along these lines through a combination of experiment and modelling. Increasingly, FBG sensors seem poised to provide high speed (sub-μs), *in situ* monitoring of material pressure and temperature under extreme conditions, providing a long sought embedded diagnostic for dynamic extremes.

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