Ultrafast Fabry–Perot fiber-optic pressure sensors for multimedia blast event measurements

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A shock wave (SW) is characterized as a large pressure fluctuation that typically lasts only a few milliseconds. On the battlefield, SWs pose a serious threat to soldiers who are exposed to explosions, which may lead to blast-induced traumatic brain injuries. SWs can also be used beneficially and have been applied to a variety of medical treatments due to their unique interaction with tissues and cells. Consequently, it is important to have sensors that can quantify SW dynamics in order to better understand the physical interaction between body tissue and the incident acoustic wave. In this paper, the ultrafast fiber-optic sensor based on the Fabry–Perot interferometric principle was designed and four such sensors were fabricated to quantify a blast event within different media, simultaneously. The compact design of the fiber-optic sensor allows for a high degree of spatial resolution when capturing the wavefront of the traveling SW. Several blast event experiments were conducted within different media (e.g., air, rubber membrane, and water) to evaluate the sensor’s performance. This research revealed valuable knowledge for further study of SW behavior and SW-related applications. © 2013 Optical Society of America

1. Introduction

Blast-induced traumatic brain injuries (bTBIs) caused by a shock wave (SW) may result in a plethora of physical, cognitive, emotional, and behavioral problems, with the possibility of permanent disability or death [1,2]. Recently, a significant effort has been made to model a bTBI in vitro system [3,4] and to understand the propagation of blast events and their effects to bTBI [5–8].

An SW can be qualitatively characterized as a nonlinear, transient, large amplitude, pressure disturbance with a positive pressure duration on the scale of a microsecond. Due to their unique interaction with tissues and cells, SWs have been applied to a variety of medical treatments, such as urology, musculoskeletal disorders, brain-neurosurgery, cancer treatments, and cerebral embolism therapies [9,10]. Several million patients have been treated worldwide since the first clinical application of extracorporeal SW lithotripsy in 1980 [11].

The conventional testing system, including sensors, SW source, and different media, was widely
developed in order to demonstrate the principle of the SW and how the SW affects biological specimens. A sensing system is embedded within a compressed air-driven shock tube (an instrument commonly used to generate SWs in a laboratory setting), to capture the traveling wavefront. In order to accurately measure the rapid pressure change during a blast event, the pressure sensors used must possess a fast dynamic response and miniature size in order to achieve high temporal and spatial resolution, respectively.

Extensive studies related to SW measurements within air-driven shock tubes and real explosion using fiber-optic pressure sensors have been conducted [6,12–14]. Compared with traditional piezoelectric-based sensors [15], fiber-optic pressure sensors have the advantage of fast dynamic response, miniature size, light weight, ease of installation, and immunity to electromagnetic interference.

In this paper, an ultrafast fiber-optic sensor is presented to quantify the SW dynamics within different media. Unlike other fiber-optic sensors that have limited spatial resolution due to the bulky supporting structure used for direct bonding of sensing element on their fiber head [6,13,14], the fiber-optic sensor presented in this paper has the same diameter as the optical fiber itself, which is generally 125 μm. This compact design allows for a high degree of spatial resolution during blast event measurements. The evaluation experiments discussed in this paper were performed to study the SW profile and the blast event propagation in different media. The different media were applied to emulate the different media that are present in biological tissue (e.g., skin, bone, brain). In this experiment, the SW propagated in air through a rubber membrane (representing skin) and was transmitted into a layer of water (representing body tissue composed of primarily water/blood). The results of this research provide validation for using the newly developed sensors that can be used in helping to understand bTBI and for the development of an in vitro system that may be ultimately used in conjunction with SWs for medical treatment.

2. Ultrafast Fiber-Optic Pressure Sensor

A. Sensor Principle

Figure 1 presents the structure of the fiber-optic pressure sensor based on the Fabry–Perot (FP) interferometric principle [16]. The sensor is composed of three parts: a single-mode fiber (SMF), an FP cavity that is wet etched on the end-face of a multimode fiber (MMF), and a silicon dioxide diaphragm with a well-controlled thickness. When an incident light propagates through the SMF and reaches the FP structure, the light reflects on two interfaces: one is between the SMF core and the FP cavity; the other is between the FP cavity and the silicon dioxide diaphragm. The two reflected lights will interfere with each other and generate an interference pattern. Due to the sensitivity of the silicon dioxide diaphragm to deform when it experiences changes in pressure, the interference pattern reflected from the FP structure shifts as the pressure changes. By interrogating the phase shift of the interference pattern, the pressure can be measured.

B. Sensor Fabrication

An SMF (SMF-28, Corning Incorporated, Corning, New York, USA) with core/cladding diameters of 8/125 μm was used in the fabrication of the fiber-optic pressure sensors. First, a 6 mm long section of protective coating was removed from the fiber tip using a cleaver (CT-30B, Fujikura, Japan). Second, the well-cleaved fiber was spliced with one end of an MMF and the other end of MMF was cleaved to achieve a specified thickness, as illustrated in Figs. 2(a) and 2(b).

The FP cavity structure can be fabricated through the process of wet etching, where the different etching rate between the pure silica of the fiber cladding and the germanium-doped silica of the fiber core causes the fiber core to etch faster than the fiber cladding when the fiber is placed into a sufficiently acidic solution. In this paper, the optical fiber was vertically dipped into a hydrofluoric solution (HF 49% in weight concentration) for 3 min. As shown in Fig. 2(c), after being rinsed in deionized water and dried, an air cavity was formed. In Figs. 2(d) and 2(e), the diaphragm was thermally bonded to the fiber and then the pressure sensor was removed from the ceramic stage. Figure 2(f) shows the fabricated fiber-optic pressure sensor.

By using this structure, no bulky sensing element is required, which means the sensor maintains a compact size by keeping the sensing element the same dimension as the optical fiber. The dimension of the silicon dioxide diaphragm was specially designed in order to have a fast response and achieve a high resonant frequency. The diameter of the sensing area on the diaphragm was chosen to be 68.39 μm and the diaphragm thickness was chosen to be 3 μm; therefore, the lowest resonant frequency was calculated to be 4.11 MHz according to the formula in [17].

C. Sensor Package

In this experiment, a packaging was designed to protect the fiber-optic sensor and to embed the fiber-optic sensor within the shock tube. As shown in Fig. 3, two sets of threaded holes were drilled into each shock tube chamber such that each threaded hole faced another threaded hole on the opposite side. A hole with a diameter of 130 mm for holding the ferrule in place was drilled through the middle of the
the bolt used to mate with the threaded hole. This threaded fitting was chosen since the traditional piezoelectric-based pressure sensors used with this shock tube have the same thread size. The fitting could have been made much smaller if needed. The ferrule with an inner diameter of 127 μm was placed inside the hole to hold the sensor, where the sensor was glued in the ferrule with epoxy. The bottom surface of the bolt, the ferrule, and the sensor were adjusted to sit flush with the interior surface of the shock tube.

3. Interrogation System and Sensor Calibration

The principle of the light intensity interrogation approach is introduced in [8]. Four fiber-optic pressure sensors (labeled as FPP1, FPP2, FPP3, and FPP4) were fabricated to be used in this experiment. In order to interrogate all the fiber-optic pressure sensors, the light source wavelength was chosen as 1552.3 nm. The interference patterns from sensors FPP3 and FPP4 (placed in water) and FPP1 and FPP2 (placed in air) are shown in Fig. 4.

Prior to the SW measurement, the four fiber-optic pressure sensors need to be calibrated in order to obtain the relationship between the change in light intensity and the corresponding change in pressure. Figure 5 shows the interrogation system setup for the sensor calibration. FPP3 and FPP4 were placed in a port immersed by water; FPP1 and FPP2 were placed into the port kept empty with air. The chamber was sealed and the pressure was precisely controlled by a highly accurate pressure controller (NetScanner Model 9034, Pressure Systems Inc.). A tunable laser (NewFocus TLB-6600, Newport) connected with a one-to-four beam splitter was introduced to excite the laser signal into all four fiber-optic sensors at the selected operating wavelength. The reflected light from each sensor was separately collected by a photodetector (PDA10CS, Thorlabs) through an optical circulator. The pressure controller was set to increase from 0 to 15 psi with an interval of 3 psi then decreased in the same manner. The increasing and decreasing cycles were repeated three times in order to evaluate the sensors’ repeatability.
Finally, the calibration result of FPP3 is shown in Fig. 6. From the figure it can be clearly observed that the sensor is repeatable with a very small variation between the increasing and decreasing cycles. Due to the nonlinearity of the response of the sensor to the pressure, a second-order polynomial fit was derived from the data. The polynomial function may be described as \( y = A + B_1 x + B_2 x^2 \), where \( A = 45.02 \), \( B_1 = -2.075 \) and \( B_2 = 0.0269 \), respectively. The adjusted R-square coefficient is calculated to be 0.999. The sensitivity is calculated as \( B_1 + 2B_2x \).

Due to the different reflection interference patterns, the remainder of the sensors show different pressure response curves with same tunable laser operating wavelength. However, they are calibrated with the same approach as FPP3, and all of them have a good repeatable performance.

4. Experimental Setup

In order to test the performance of the fabricated pressure sensors, the SW profiles generated by a shock tube traveling within two different media were measured in several tests. Two chambers, made from schedule 80\# aluminum, were clamped together and connected to the shock tube as shown in Fig. 7. A rubber diaphragm separated the interface of the two aluminum chambers to isolate both chambers from one another, such that chamber #1 was filled with air to simulate the control environment and chamber #2 was filled with water (representing body tissue composed of primarily water/blood). Four fabricated pressure sensors and four reference pressure sensors (Model\# 102B06, PCB Piezotronics, Inc.) were mounted onto the chamber through the threaded holes of the side of the chamber. The fiber-optic sensors and the piezoelectric sensors were positioned facing opposite to each other in order to obtain the propagating SW simultaneously. The photograph of the experiment setup is shown in Fig. 8.

The fiber-optic sensors were interrogated by the light intensity interrogation method described previously and the reflected light signals from the fiber-optic sensors were sampled by a computer using a data acquisition (DAQ) system (M2i.4032, Spectrum GmbH), where the sampling rate of the DAQ system was set to 50 MHz and the photodetector (PDA10CS, Thorlabs) was set with 20 dB gain. When the SW was generated by the shock tube, the SW triggered the DAQ to record the acoustic pressure of the wave using the fiber-optic and reference sensors.

5. Experimental Results

A. Resonant Frequencies of the Sensor in Air

The resonant frequency of the sensor determines the practical maximum frequency the fiber-optic sensor is able to measure. According to the rule of thumb for diaphragm-based pressure sensors, the maximum frequency the sensor is able to accurately measure is approximately 20\% of its first resonant frequency. Using a formula obtained from other works \([17,18]\), the excited resonant frequency of the fiber-optic sensor in air applied in this experiment was 4.11 MHz. Therefore the sensor is able to capture data with high fidelity up to 822 kHz. In order to essentially eliminate the oscillations that are attributed to the mechanical resonance of the diaphragm and reveal the SW, a fifth-order Butterworth low-pass filter (3 MHz cutoff) is applied to the results from FFP1 and FFP2 shown in this section.

B. Resonant Frequencies of the Sensor in Water

When the sensor is immersed in water, the resonance frequency is appreciably reduced due to the inertia of the fluid. This is called the deterioration of the frequency response due to the fluid and the equation in \([17,18]\), should be replaced by

\[
 f_0 = \frac{1}{\sqrt{1 + \beta}} \frac{a_{00}}{4\pi} \frac{E}{3w(1-\mu^2)} \left[ \frac{h}{(d/2)^2} \right],
\]

\[
 \beta = 0.669 \frac{ed}{2h},
\]

where \( a_{00} \) is a constant related to the vibrating modes, \( w \) is the mass density of the diaphragm material, \( E \) is Young's modulus, \( \mu \) is Poisson's ratio, \( h \) is the thickness of the diaphragm, and \( d \) is the diameter of the diaphragm. The value of those parameters can be found in \([17,18]\). \( e = 0.38 \) is the ratio of the density of the water to the density of the silicon dioxide.
diaphragm. Therefore, the excited resonant frequency of the fiber-optic sensor in water is 2.08 MHz. A fifth-order Butterworth low-pass filter (1.5 MHz cutoff) is applied to the results from FFP3 and FFP4 shown in this section.

C. Capability of Capturing Shock Waves in Different Media

After the SWs were generated in the shock tube, there were multiple peaks due to the multiple reflections along the shock tube and the aluminum chamber. Figure 9 shows the first cycle of the SW dynamics that were captured by the fiber-optic sensors. Figure 9(a) shows the SW pressure profile in the time period from 0 to 10 ms. Figure 9(b) shows the zoom-in plot of Fig. 9(a) with the time scale set from 0 to 1.2 ms. From the figures, it can be seen that the fiber-optic sensor has the capability of capturing the profiles of the rapidly changing SWs traveling within the different media.

In Fig. 10, the first cycle of the SW dynamics that were captured by the fiber-optic sensors and the reference sensors is presented. From the figures, the signal from the fiber-optic sensor was similar to the one from the reference sensor including the rise part and the decay part.

D. Shock Wave Dynamics in Different Media

From Fig. 9(a), the signals from FPP3 and FPP4 clearly indicate that the water medium significantly changes the SW dynamics compared to the wave propagating in air. The additional peaks in the time domain response are likely due to the reflections of the wave in the water cavity due to the end plate and rubber diaphragm inducing a modal response. The volume of the water cavity is smaller than the air cavity and therefore the in-water acoustic modes will be excited at a higher frequency relative to the air cavity. Another possible explanation for the difference between the in-air and in-water response is
cavitation. When an SW is propagating through water, a water vapor bubble can result due to the rarefaction of the fluid. As the over-expanded bubble collapses another SW may result [19]. The presence of cavitation has not been verified and is beyond the scope of this work.

Moreover, from Fig. 9(b), it can be seen that the rise time of the fiber-optic sensors in air was different than the fiber-optic sensors in water. The rise time for the signal measured by FPP1 within the air chamber was 15 μs and the rise time of the signal measured by FPP3 within the water chamber was 200 μs. This is largely attributed to the density of the fluid in which water is significantly more dense than air and requires a longer duration to accelerate the same volume of fluid for a given applied force or pressure.

E. Shock Wave Propagation Velocity in Different Media

It can be observed from Fig. 9(b) that the SWs from different fiber-optic sensors have different start times, which agree with their position along the test chambers. In order to determine the different time interval between two consecutive fiber-optic sensors within each chamber, the pressure signals between 0 and 0.4 ms were extracted and are shown in Fig. 11.

Figure 11 depicts the SW dynamics in air and water. The time interval between the response of FPP3 and FPP4 was calculated to be 0.033 ms. The distance between two consecutive threaded holes on chamber #2 was same as chamber #1. Therefore, the SW propagation velocity in water was 1540 m/s at 25°C, which is also slightly higher than the speed of sound in water (1496 m/s at 25°C).

The interpretation of this finding can be found in [20]. Unlike ordinary acoustic waves, the velocity of an SW varies with its amplitude. At the beginning, the velocity of an SW is always greater than the speed of sound in air and fluid, and as the amplitude of the SW decreases, so does its velocity. When the SW velocity reduces to the normal speed of sound in its appropriate media, the SW dies out and is reduced to an ordinary acoustic wave.
6. Conclusions
This paper presents an ultrafast fiber-optic pressure sensor that is based on the FP interferometric principle, which can measure rapidly changing pressure waves traveling within multimedia. A shock tube experiment was performed at the Natick Soldier Research, Development and Engineering Center (NSRDEC) in Natick, Massachusetts. A special package was designed to protect the sensor and mount the sensor. In the experiment, multimedia blast event experiments were conducted to evaluate the performance of the sensor. The sensors were formed as a sensor array and mounted into chambers filled with different media (air and water) and connected to a shock tube. The results demonstrated that the sensor has the ability to capture the dynamic pressure transient during a very fast multimedia blast event.

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