Fibre Bragg Grating sensor for shock wave diagnostics

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Abstract. We measured the response of short FBGs to a weak planar shock wave. The combined effect of the Photo-Elastic effect and the FBG strain was estimated theoretically depending on its orientation with respect to shock front (for 1550 nm FBG, parallel: 0.9 nm/kbar, perpendicular: -1.4 nm/kbar). The experimental results imply that the FBG/fibre survives for more than 1 μs at 5 kbar shock stress, and that our assumptions about the FBG behaviour under dynamic loading are valid, though more work is needed to fully quantify the effect.

1. Introduction
Shock wave techniques are widely used for studying the dynamic properties of materials. The rapidly applied pressure increases the density and the temperature of the material under study, thus opening a doorway for revealing its EOS, phase diagram, dynamic strength etc. Two key experimental factors govern this research field, first, the ability to properly load the material under test to the desired pressure, with means such as high velocity impact or by the use of high explosives, and second, to apply proper diagnostics. Fibre Bragg Grating (FBG) sensors may address the diagnostic needs by measuring the velocity of the shock wave and by, in situ, measuring the applied dynamic stress.

FBG sensors were recently applied in shock-wave research [1, 2]. The main advantages of FBG sensors for shock-wave diagnostics are:
- Minimal disturbance (100-200 μm in diameter, and the gratings may be 1-few mm long).
- Survivability at relatively high pressure shocks
- Inherent immunity to EMI.

2. Influence of a shock wave on FBG characteristics
The nominal Bragg wavelength $\lambda_B$ reflected from a fibre Bragg grating is given by [3]:

$$\lambda_B = 2\Lambda n_{eff} \quad \Rightarrow \quad \delta\lambda_B / \lambda_B = \delta n_{eff} / n_{eff} + \delta\Lambda / \Lambda$$

(1)

where $\Lambda$ is the grating period and $n_{eff}$ is the (effective) refractive index of the fibre core. Both $\Lambda$ and $n_{eff}$ are affected by the shock wave due to changes in density and temperature of the fibre core, yielding a complex dependence of $\lambda_B$ on the shock. We will discuss each phenomenon separately and then merge them into a single expected effect for some typical cases.
2.1. Influence of relative orientation
We expect to find dependence of the FBG response not only on the absolute shock stress but also on its orientation with respect to the shock front. Consider a planar shockwave front impacting a fibre embedded in the target medium along its axis. The fibre, and hence the grating inscribed into it, will be compressed along the axis. This effect will not take place for a planar shock wave striking the fibre from its side.

For intermediate angles between the wave propagation direction and the fibre axis, it may be assumed, at least to first order, that only the stress component along the fibre axis will have a dimensional effect on the grating. In the following text we will address only two cases: shock wave propagation is either along or perpendicular to the fibre axis.

2.2. Influence of pressure

2.2.1. Photo-Elastic effect. Material density changes affect its optical refractive index (and birefringence, which we neglect). By the Gladstone – Dale relation the effect may be quantified in fused silica as:

\[ \frac{\delta n_{\text{eff}}}{n_{\text{eff}}} = 6 \times 10^{-4} \text{ per kbar} \]  

(2)

2.2.2. Material compression. In our research we tested the response of the FBG under relatively low dynamic pressures of less than 1 GPa. These values are within the elastic regime since the Hugoniot elastic limit of fused silica is \(-7\) GPa [3], therefore we can use Young’s module in our stress/strain calculations. The Young’s modulus of fused silica is 70 GPa, which translates to a uniaxial compression ratio of the FGB’s grating period:

\[ \frac{\delta A}{A} = -1.5 \times 10^{-3} \text{ per kbar} \]  

(3)

2.2.3. Combination of pressure effects. As seen, the two effects affect the grating in opposite manners, with the compression effect having a larger absolute value. Thus for a shock front which is parallel to the fibre axis, where only the photo-elastic effects influences the grating, we expect an increase in the returned wavelength from the grating by:

\[ \frac{\delta \lambda_B}{\lambda_B} = \frac{\delta n_{\text{eff}}}{n_{\text{eff}}} = 6 \times 10^{-4} \text{ per kbar} \]  

(4)

which translates to a shift of \(0.9 \text{ nm/kbar}\) at a central wavelength of \(\lambda_B = 1,550\) nm. For a shock front perpendicular to the fibre axis, where the two effects are present, we expect a decrease of:

\[ \frac{\delta \lambda_B}{\lambda_B} = \frac{\delta n_{\text{eff}}}{n_{\text{eff}}} + \frac{\delta A}{A} = -0.9 \times 10^{-3} \text{ per kbar} \]  

(5)

which translates to a shift of \(-1.4 \text{ nm/kbar}\) at a central wavelength of \(\lambda_B = 1,550\) nm.

2.2.4. Influence of Temperature. The temperature response of FBGs is very well known, both from theory and experiments [3]. It is approximately 12 pm/°C at a central wavelength of \(\lambda_B = 1,550\) nm. For weak shock we can express the shock temperature \(T_H\):

\[ T_H = T_0 \exp(\gamma \varepsilon) \]  

(6)
where \( T_0 \) stands for the ambient temperature, \( \gamma \) for the Gruneisen parameter of fused silica (~1.5) and \( \varepsilon \) for the strain. In our experiments the shock pressure was under 1 GPa corresponding to a temperature rise of less than 6.5 °C and a resulting spectral shift of less than 0.1 nm. Thus here we can neglect the thermal effect which should, however, be addressed for stronger shock experiments.

3. Experimental Set-Up

We used a gas gun (25 mm diameter) to launch a LEXAN impactor to velocities of ~300 m/s. Two FBGs with centre wavelengths of 1552.5 nm were embedded in the PMMA target with different orientations with respect to the planar shock front (parallel and perpendicular) as seen in figure 1. The FBG’s centres were placed 2 mm from the impact plane of the target. A gold coated PMMA window was used to measure the particle velocity (VISAR). Four piezoelectric pins placed on the front end of the target were used for tilt estimation and triggering. The FBGs used in our experiments were ordinary commercial items written in a single mode fibre (SMF-28), with the exception of their length which was about 1 mm. The short length was necessary in order to better localize the measurements. The outcome of this short FBG is somewhat smaller reflection (~85%) and a larger spectral width of the reflected spectrum (0.75 nm FWHM) than can be achieved with longer (10 mm) gratings.

The electro-optical system’s function is to track the spectral change of the two FBGs reflections during the shock impact. High speed spectral analysis may be achieved by elaborate interferometric means, but we adopted a more simple approach, involving “staring detectors”, each in a separate spectral window as depicted in figure 2.

**Figure 1.** The PMMA target setup; Left: Schematics - side view. Right: Photo – front view.

**Figure 2.** Electro-optical system layout; Left: Concept. Right: Implementation.
The signal reflected from the FBG (carrying information on its current situation encoded into its spectrum) is diverted by the circulator to the readout system, comprising 5 add-drop filters in sequence. Each filter diverts output wavelengths fitting into its spectral window to a detector, while transferring all other wavelengths to the next filter. Each filter has a spectral FWHM bandwidth of 1.2 nm. The last filter acts like the others, but its “through” output serves as a residue port, including all the wavelengths that do not fit into any of the 5 spectral windows. All these 6 optical outputs feed 6 high-speed detectors (rise-time of 30 ns).

4. Experimental results

4.1. FBG perpendicular to shock wave front
In figure 3 we show the reading of the electro-optical system from the FBG which is perpendicular to the shock front. The projectile velocity was 296±6 m/s and the matched pressure ~ 4.8±0.2 kbar:

![Figure 3](image)

**Figure 3.** Experimental results for perpendicular FBG; Left: System output. Right: Colour code of lines.

The response of the 1,552.5 nm filter drops to zero in ~300 ns. This corresponds to the time needed for the shock front travelling at 2,450±50 m/s [5] to pass the full length of the FBG which is 1 mm. During this time interval we find spectral broadening of the FBG reflection while shifting to shorter wavelengths. The last filter signal at 1,546.1 nm indicates a shift of $\Delta \lambda \leq -6.4$ nm. Using the approximate relation between wavelength shift and stress (5) of -1.4 nm/kbar we find that the stress $P \geq 4.6$ kbar.

Due to lack of shorter wavelengths filters we were unable to determine if the FBG response shifted to even shorter wavelengths. The spectral broadening can be explained by a stress gradient and a shorter effective FBG per reflected wavelength during the passage of the shock over the full FBG length.

4.2. FBG parallel to shock wave front
In figure 4 we show the reading of the electro-optical system from the FBG which is parallel to the shock front. We can see the spectral shift of the FBG reflection to longer wavelengths $\Delta \lambda \geq 1.6$ nm. Using the approximate relation between wavelength shift and stress (4) of 0.9 nm/kbar we find that the stress was $P \geq 1.8$ kbar.

The response of the 1,552.5 nm filter drops to zero in ~300 ns. A closer observation of the signal reveals a fast response at the first 20 ns (to 75 %) followed by a much slower response (to 10 % at 270 ns). At a shock velocity of 2,450 m/s the passage over the FBG core diameter (10µm) is ~ 4ns, adding the rise time of the wave front ~20 ns and the detectors response time we would expect a
signal drop in ~30 ns. We believe that a mechanical mismatch between the fibre insert and the PMMA target may cause this effect by introducing rarefaction waves from the free surfaces of the gaps. In future experiments we plan a tighter fitting between those parts.

Figure 4. Experimental results for parallel FBG; Left: System output. Right: Colour code of lines.

In the present setup there was only one filter for longer wavelengths (1,554.1 nm) so we were unable to determine if the FBG response shifted to longer wave lengths. In the improved setup we are planning to solve this issue by rearranging the add-drop filters. In addition we plan to reduce by a factor of 10 the response time of the photo detectors.

5. Conclusions and future work
In this work we measured the response of short FBGs to weak planar shock waves. We showed that the FBG/fibre survives for more than 1 \( \mu s \) under 5 kbar shock stress. The experiments confirm the assessment that the FBG response depends on its orientation with respect to shock front. The combination of the Photo-Elastic effect and the FBG strain was estimated theoretically and compared to the experimental data. The results show that our assumptions about the FBG behaviour under dynamic loading are valid, though more work is needed to fully quantify the effect.

In the near future we plan to conduct a second series of experiments with improved mechanical and electro-optical design. The main modifications are: reducing temporal response, fine adjustments of the add-drop filters and better mechanical fitting. We also plan to increase the shock stress up to ~1 GPa.

We believe that there is a real potential for the development of shock stress diagnostics based on FBG for shock waves up to the fused silica Hugoniot elastic limit.

References
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