Research on the fiber Bragg grating sensor for the shock stress measurement

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(Received 17 July 2011; accepted 15 September 2011; published online 26 October 2011)

A fiber Bragg grating (FBG) sensor with an unbalanced Mach-Zehnder fiber interferometer for the shock stress measurement is proposed and demonstrated. An analysis relationship between the shock stress and the central reflection wavelength shift of the FBG is firstly derived. In this sensor, the optical path difference of the unbalanced Mach-Zehnder fiber interferometer is ~ 3.1 mm and the length of the FBG is 2 mm. An arctangent function reduction method, which can avoid sine function's insensitive zone where the shock stress measurement has a reduced accuracy, is presented. A shock stress measurement of water driven by one stage gun (up to 1.4 GPa), with good theoretical accuracy ($\sim 10\%$), is launched. © 2011 American Institute of Physics. [doi:10.1063/1.3648123]

I. INTRODUCTION

It is necessary to precisely measure the shock stress, the essential dynamic parameter of a material, in some special field, for example, the shock and detonation physics, high energy density physics, and geophysics.^{1,2} The conventional piezoresistive (carbon, manganin, ytterbium) and piezoelectric (X-cut quartz, lithium niobate, polymer-gage, polyvinylidene fluoride) sensors³⁻⁵ record directly voltage or current, which can be converted to stress. In some particular cases,^{6,7} these conventional pressure sensors have several disadvantages such as electromagnetic interference (EMI), low bandwidth, and inconvenience for the shock stress measurement in some special materials. Several qualities of the fiber Bragg grating (FBG) make it very attractive for the shock stress measurement.⁶⁻⁸ The FBG have a very small diameter (125 μm typically, with a polyimide coating of 5–10 μm for protections) that has a minimal effect on the shock behavior of the material. The FBG has the unique potential to measure the changes in the shock stress as the shock wave front moves through the interfaces between two different materials. In addition, the FBG has an advantage of being immune to EMI and high bandwidth.

The FBG in its most basic form consists of a periodic modulation of the refractive index along a single mode fiber. The FBG is a distributed reflector, acting as a narrowband reflection filter. The maximum reflectivity of the FBG occurs at a wavelength that matches the Bragg condition⁶

$$\lambda_B = 2n\Lambda, \quad (1)$$

where the wavelength λ_B is the free-space center wavelength of the input light that will be back reflected from the FBG, n is the effective refractive index of the fiber core, and Λ is the FBG period.

When an elastic stress wave impinges on a FBG at normal incidence, the refractive index of the fiber core and the FBG period are modulated due to the mechanical strain in the fiber

through the elasto-optic effect. The stress can be written as a function of the spectral shift of the FBG:⁷

$$\sigma = \frac{\Delta\lambda_B}{-(1-2\nu)/E + n^2(1-2\nu)(2p_{12} + p_{11})/2E}, \quad (2)$$

where E and ν are the Young's modulus and the Poisson's ratio, σ is the stress that is caused by the elastic wave, p_{11} and p_{12} are components of the strain-optic tensor of the FBG, and $\Delta\lambda_B$ is the spectral shift of the FBG. Equation (2) shows that the stress is directly proportional to the spectral shift of the FBG on condition that the amplitude of the stress wave does not exceed the elastic limit of the FBG.

In this work, an analysis relationship between the shock stress and the central reflection wavelength shift of the FBG is firstly derived. The FBG sensor with an unbalanced Mach-Zehnder fiber interferometer is demonstrated. The optical path difference (OPD) of the unbalanced Mach-Zehnder fiber interferometer is ~ 3.1 mm. The length of the FBG is 2 mm and the 3dB bandwidth is 0.3 nm. An arctangent function reduction method, which can avoid sine function's insensitive zone where the measurement stress has a reduced accuracy, is presented. An experimental demonstration has been performed with this sensor to measure the shock stress (up to 1.4 GPa) of water driven by one stage gun.

II. PRINCIPLE OF OPERATION

The differential expression of Eq. (1) is as following:

$$\frac{\Delta\lambda_B}{\lambda_B} = \frac{\Delta\Lambda}{\Lambda} + \frac{\Delta n}{n}. \quad (3)$$

When the amplitude of the stress wave, which is incident on a FBG at normal direction, greatly exceeds the dynamic flow strength of the FBG, the disturbance front will be steep and it leads to a shock front, which is defined as a discontinuity in pressure, temperature (or internal energy), and density. It is possible to derive the following equation:⁹

$$\varepsilon = \frac{\Delta\Lambda}{\Lambda} = -\frac{\rho - \rho_0}{\rho}, \quad (4)$$

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where ε is the strain of the FBG; ρ_0 , the ambient density, is 2.02 g/cm^3 ; and ρ is the density behind the stress wave front.

The refractive index n of the FBG is approximately linear in density under the shock loading:¹⁰

$$n = a + b\rho, \quad (5)$$

where a and b are related to the wavelength of the light source. When the wavelength of the light source is 1550 nm, the values of a and b are approximately 1.04 and 0.18.¹⁰

Substituting Eqs. (4) and (5) into Eq. (3), we obtain the spectral shift of the FBG as a function of the strain:

$$\frac{\Delta\lambda_B}{\lambda_B} \approx \frac{a}{a + b\rho_0} \approx 0.7\varepsilon. \quad (6)$$

The stress-strain equation is as following:¹¹

$$\sigma = A\varepsilon + B\varepsilon^2 + C\varepsilon^3 + D\varepsilon^4, \quad (7)$$

where σ is the stress in kilobars and the values of A , B , C , and D are 776.0, -4159 , 30340, and 69260.

Substituting Eq. (6) into Eq. (7), we obtain

$$\sigma = A \left(1.4 \frac{\Delta\lambda_B}{\lambda_B} \right) + B \left(1.4 \frac{\Delta\lambda_B}{\lambda_B} \right)^2 + C \left(1.4 \frac{\Delta\lambda_B}{\lambda_B} \right)^3 + D \left(1.4 \frac{\Delta\lambda_B}{\lambda_B} \right)^4. \quad (8)$$

So we can calculate the shock stress through the wavelength shift that can be measured by the unbalanced Mach-Zehnder fiber interferometer.

III. INSTRUMENTATION

The unbalanced Mach-Zehnder fiber interferometer used for the wavelength shift measurement is shown in Fig. 1. The light from an amplified spontaneous emission (ASE) broadband light source (100 mW, 1525–1565 nm) is coupled into port A of the circulator and exits from port B. Then the light is transported into the FBG and a small part of it is reflected. The reflected light launched into port B exits from port C and is divided into two lights by a 2×2 coupler. The two lights transport through two different paths and are coupled by a 3×3 coupler. The outputs of the 3×3 coupler are converted by three detectors.

The OPD of the Mach-Zehnder fiber interferometer is ~ 3.1 mm. The length of the FBG is 2 mm and its 3 dB bandwidth is 0.3 nm.

Three output interferometric signals have a phase difference of $2\pi/3$.¹²

$$I_1(t) = I_0(1 + V \cos(2\pi F(t))), \quad (9)$$

FIG. 1. The configuration of the Mach-Zehnder fiber interferometer.

FIG. 2. (Color online) The schematic of test setup for measuring the shock stress of water.

$$I_2(t) = I_0(1 + V \cos(2\pi F(t) + 2\pi/3)), \quad (10)$$

$$I_3(t) = I_0(1 + V \cos(2\pi F(t) - 2\pi/3)), \quad (11)$$

where I_0 is dependent on the intensity of the light source, V is the visibility of the signals, and the fringe number $F(t)$ of the signals is governed by the following equation:¹³

$$F(t) = \frac{\Delta\Phi}{2\pi} = \frac{\Delta\lambda_B \delta D}{\lambda_B^2} \approx 2 \times 10^3 \frac{\Delta\lambda_B}{\lambda_B}, \quad (12)$$

where $\Delta\Phi$ is the phase difference and δD is the OPD of the interferometer.

A schematic of test setup for measuring the shock stress of water driven by one stage gun is shown in Fig. 2. The velocity of Al flyer is 800 m/s and the sizes of Al flyer and Al target are both $\Phi 100 \times 2$ mm. The container filled in water is $\Phi 100 \times 40$ mm and is attached to the rear surface of the Al target. The distance between the FBG located in the leading end of the optical fiber and the rear surface of the Al target is 5 mm.

IV. DATA REDUCTION METHOD

It is possible to derive two signals from Eqs. (10)–(12)

$$S_1(t) = -3 \frac{I_2(t) + I_3(t)}{I_1(t) + I_2(t) + I_3(t)} = \cos(2\pi F(t)), \quad (13)$$

$$S_2(t) = -\sqrt{3} \frac{I_3(t) - I_2(t)}{I_1(t) + I_2(t) + I_3(t)} = \sin(2\pi F(t)). \quad (14)$$

Substituting Eq. (13) into Eq. (14), we obtain

$$F(t) = \frac{1}{2} \left[n + \arctan \left(\frac{S_2(t)}{S_1(t)} \right) \right], \quad (15)$$

FIG. 3. (Color online) Three experimental signals.

FIG. 4. (Color online) Two normalized signals.

FIG. 5. (Color online) The Lissajous ellipse.

FIG. 6. The shock stress of water.

where n is an integer which can be determined by the logical means if the contrast is maintained through the measurement.¹⁴

Substituting Eqs. (12) and (15) into Eq. (8), the value of the shock pressure can be calculated.

V. THE SHOCK STRESS MEASUREMENT

Figure 3 shows three experimental signals of the FBG sensor and their effective duration is $\sim 0.5 \mu\text{s}$. S_1 and S_2 are two normalized signals generated by three experimental signals according to Eqs. (13) and (14) in Fig. 4. Figure 5 is the Lissajous ellipse which is generated from S_1 as X axis and S_2 as Y axis. As S_1 and S_2 are modulated by the shock stress, the coordinate (S_1, S_2) is rotating on the Lissajous ellipse when the shock stress varies with time. The phase difference ξ between S_1 and S_2 , which is obtained by the direct ellipse fitting method,¹⁵ is 75° . When two normalized signals are not in quadrature, Eq. (15) is modified by the following equation:¹⁶

$$F(t) = \frac{1}{2} \left\{ n + \frac{1}{\pi} \arctan \left[\left(\frac{S_2}{S_1} \right) \sec \left(\frac{\pi}{2} - \xi \right) + \tan \left(\frac{\pi}{2} - \xi \right) \right] \right\}. \quad (16)$$

According to Eq. (12), the phase resolution is dependent on the fringe ambiguity, which is essentially a question of angular resolution on the Lissajous ellipse. Visual fringe estimates better than 0.06 ($\Delta\Phi \approx 2\pi/16$) are easily achievable, and the limiting uncertainty is generally quoted as 0.02 ($\Delta\Phi \approx 2\pi/50$) or better.¹⁴

Figure 6 is the shock pressure of water measured by the FBG sensor. The maximum pressure measured by this sensor is $1.4 \pm 0.1 \text{ GPa}$, which is 10% different from that of the numerical calculation.

VI. CONCLUSION

The experiment has shown that the shock stress of water driven by one stage gun can be successfully detected with the

FBG sensor. An analysis relationship between the shock stress and the central reflection wavelength shift of the FBG is firstly derived, which is especially important for the shock stress measurement. This relationship does not only take into account the influence of the shock stress but also that of the temperature. The arctangent function reduction method, which can avoid sine function's insensitive zone where the shock stress measurement has a reduced accuracy, is presented.

ACKNOWLEDGMENTS

We are grateful to many colleagues for providing helpful comments and would especially like to thank the assistance given to us by D. Li of the Vienna College in Austria.

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