Detection of Tsunami Wave Generation and Propagation Using Fiber Bragg Grating Sensors

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Abstract — **This paper describes the design and development of a Fiber Bragg Grating (FBG) sensor system for monitoring tsunami waves generated in the deep ocean. An experimental setup was designed and fabricated to simulate the generation and propagation of a tsunami wave. The characteristics and efficiency of the developed FBG sensor was evaluated with a standard commercial *Digiquartz* sensor. For real time monitoring of tsunami waves, FBG sensors bonded to a cantilever is used and the wavelength shifts ($\Delta\lambda_B$) in the reflected spectra resulting from the strain/pressure imparted on the FBGs have been recorded using a high-speed *Micron Optics* FBG interrogation system. The parameters sensed are the signal burst during tsunami generation and pressure variations at different places as the tsunami wave propagates away from the source of generation. The results obtained were compared with the standard commercial sensor used in tsunami detection. The observations suggest that the FBG sensor was highly sensitive and free from many of the constraints associated with the commercial tsunameter.**

I. INTRODUCTION

Tsunamis are water waves triggered by impulsive geologic events such as sea floor deformation, landslides, slumps, subsidence, volcanic eruptions, etc. Tsunamis can inflict significant damage and causalities both early (near-field) and after evolving over a long propagation distances (far-field) impacting distant coastlines [1].

Detection of tsunami generation and propagation is of paramount importance for protecting coastal population, coastal structures and natural environment [2]. Accurately and reliably predicting the initial waveform and the associated coastal effects of tsunamis remains one of the most important problems in geophysics and instrumentation. Though a solution for this problem is partly obtained from routine numerical computation or data collection, their limitations are usually overcome by proper experimental validations. Investigations in this regard have become highly interdisciplinary with contributions ranging from instrumentation and applied science to coastal zone management. Most comprehensive current studies involve number of marine surveys on costal tsunamigenic underwater faults, slump geology, sediment stability, under water ground failures and seismic considerations.

About a decade ago it was believed that the process of tsunami wave generation was adequately understood and could be accurately predicted. However, after the recent tsunami disasters, it now is clear that this is not the case, especially with near-field which is the most crucial parameter to be detected for early warning. One of the most challenging aspects in the tsunami study is the way the tsunami wave is simulated in the laboratory. In this work a simple set up for generating tsunami waves in the laboratory has been developed. Using this set up, an attempt to detect the early or near-field tsunami waves as well as the propagated or far-field tsunami waves with varying pressure heads using a Fiber Bragg Grating (FBG) sensor system.

The principle employed is that the central (Bragg resonance) wavelength of the FBG responds to the changes in the pressure heads during the generation as well as during propagation of a tsunami wave. To measure the change in the reflected wavelength of the FBG sensor, which is then interpreted to a respectable strain value, a Micron Optics SM 130-700 FBG sensor interrogation system has been used. The results obtained have also been compared against the standard commercial tsunameter (*Digiquartz*) and are found to be in good agreement.

The primary aim of this work is to explore simpler methods of generating near-field and far-field tsunamis and detection of the same using a FBG sensor system which has distinct advantages like immunity to electromagnetic interference, higher sensitivity, better response characteristics and the possibility of low cost distributed measurement over large distances with negligible signal degradation.

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II. SENSOR INSTRUMENTATION

A. Working Principle of a FBG Sensor

A FBG is a periodic modulation of the refractive index of the core of a single-mode photosensitive optical fiber [3]. The inscription of Bragg gratings onto the fiber core can be realized by several techniques such as interferometric method, point-by point writing, phase-mask technique, etc.

The phase mask method employed in this work, is one of the most effective methods for inscribing Bragg gratings in a photosensitive fiber. This technique employs a diffractive optical element (phase mask) to spatially modulate the writing beam (UV) which will interfere in the core of an optical fiber [4]. The simplicity of using only one optical element provides a robust and inherently stable method of reproducing Fiber Bragg Gratings.

A broad band light launched into the FBG, will be scattered by each grating plane. The light reflected from each of the subsequent planes will constructively interfere for a particular wavelength, λ_B, for which the Bragg condition shown in (1) is satisfied:

$$\lambda_B = 2\, n_{\text{eff}}\, \Lambda \tag{1}$$

In other words, the Bragg resonance wavelength λ_B, is the free space centre wavelength of the input light that will be back-reflected from the Bragg grating. Here, n_{eff} is the effective refractive index of the fiber core at the free space centre wavelength and Λ is the spacing between the gratings. It is seen from (1) that the Bragg grating resonance depends on the effective index of refraction of the core (n_{eff}) and the periodicity of the grating (Λ). The effective index of refraction, as well as the periodic spacing between the grating planes, is affected by external perturbations such as strain and temperature. The shift in the Bragg grating centre wavelength due to strain and temperature changes is given by

$$\Delta\lambda_B = 2\left[\Lambda\,\frac{\partial n_{\text{eff}}}{\partial l} + n_{\text{eff}}\,\frac{\partial\Lambda}{\partial l}\right]\Delta l + 2\left[\Lambda\,\frac{\partial n_{\text{eff}}}{\partial T} + n_{\text{eff}}\,\frac{\partial\Lambda}{\partial T}\right]\Delta T \tag{2}$$

The first term in above equation represents the strain effect on an optical fiber and the second term represents effect of temperature. One of the simple ways of compensating temperature effect is to use a sacrificial FBG in unstrained condition, close to the sensing FBG, whose Bragg wavelength is subjected only to the influence of the temperature [5].

The strain effect term shown in (2) corresponds to a change in the grating spacing and the strain-optic coefficient induced change in the refractive index. The strain effect term from the above equation may be expressed as

$$\Delta\lambda_B = \lambda_B\left[1 - \frac{n^2}{2}\left[P_{12} - \nu(P_{11} - P_{12})\right]\right]\varepsilon_Z \tag{3}$$

Where P_{11} and P_{12} are components of the strain optic tensor, ν is the Poisson's ratio and $\varepsilon_Z = \partial l/l$.

B. FBG Interrogator

As mentioned earlier, a micron optics SM 130-700 FBG sensor interrogation system has been used in the present work, which can record data at a rate of 1 kHz with a resolution of 1 $\mu\varepsilon$. The performance of this interrogator module is characterized by high data acquisition rates, high sensitivity and repeatability.

C. Digiquartz Depth Sensor

A commercially available Digiquartz depth sensor (tsunameter) [6] with a typical accuracy of 0.01% has also been used in the present study, to compare and validate the results obtained from the FBG sensor. The Digiquartz depth sensor uses a precision quartz crystal resonator whose frequency of oscillation varies with pressure-induced stress. High accuracy, resolution, and stability make these sensors ideal for under water applications like ocean depth detection and tsunami wave sensing.

III. EXPERIMENTAL SETUP AND PROCEDURE

On the basis of origin, tsunami waves have been categorized in to seismic activity waves (tsunamis) and atmospheric disturbances waves (meteo-tsunamis). Despite their differences in origin, both types of tsunami waves generate similar waves and produce similar catastrophic effects in coastal areas. Due to these similarities, it is often difficult to distinguish between these two phenomena, without knowing the exact source characteristics. In this experiment, seismic activity waves generated by the ocean bed collapse, has been simulated under the lab conditions in order to test the feasibility of FBG sensors.

Two separate experiments have been conducted in a Perspex water tank, shown in Fig 1 (1.8m length × 0.3m width × 0.6m height) for generation and propagation of the tsunami wave. Each experiment required a special technique and idea as the experiment has been carried out under spatial constrains of the laboratory. In both the experiments, FBG sensors have been tested simultaneously with the Digiquartz tsunameter.

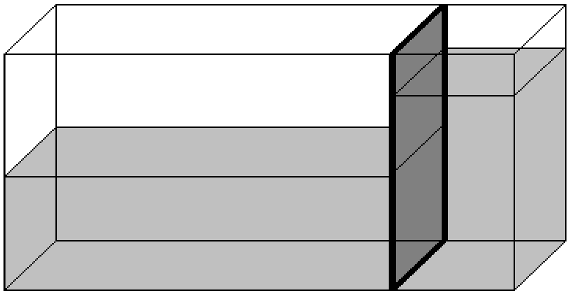

Figure1. Schematic of laboratory setup for generation and propagation of the tsunami wave

A. *Tsunami Wave Generation Technique*

In the first method, a filled air-bag sandwiched between two metal plates is kept at the bottom of the tank. The air-bag is suddenly deflated by actuating an outside valve causing a sudden collapse of the metal plates which in turn produces a transient displacement of water generating tsunami waves. This simple method mimics the process of tsunami wave generation from the seismic disturbances. The sudden release of air from the air bag characterizes the tremor; whereas the ocean bed collapse is mimicked by the collapse of the heavy metal plate.

B. *Tsunami Wave Propagation Technique*

The generation of a tsunami wave is due to the vertical shift in the ocean water level. The greater an earthquake is, the larger is the vertical displacement and consequently, the greater is the pressure of the tsunami generated and propagated. For simulating a tsunami wave with different pressure heads which will mimic a real time scenario of wave propagation, a tank with two separate compartments has been used. In this experiment, a water tank with two compartments separated by a vertical plate (gate), which can be manually lifted, has been employed. If the two compartments are filled with different water levels and the gate is suddenly lifted, gravity waves are created which mimic a tsunami propagating along the length of the tank.

In a typical experiment, one compartment is filled with a constant water level just sufficient for the generated tsunami wave to propagate while the other is filled with varying water levels. Upon lifting the gate, depending on the difference in water level between the two compartments, tsunami waves with different pressure heads are generated. Experiments are conducted by varying water volume differences between 1 liter to 3 liters (insteps of 0.5 liters), to generate tsunami waves of pressure varying from 0.0005 decibar to 0.0040 decibar. Though the pressure range can be extended by increasing the volume difference between the two compartments, it is difficult to achieve this in a laboratory due to special and experimental constraints.

In the present study, the similarities between the two types of tsunami generation (tsunamis and meteo-tsunamis) enabled us to consider the seismic activity as the source of disturbance for generation of tsunami wave.

IV. SENSOR PACKAGING

Generally, the FBG sensor fabricated in a standard single-mode optical fiber has low sensitivity to pressure, as the demodulation with a wavelength resolution of 0.1pm will provide a pressure resolution of approximately 30 kPa [7]. This may not be sufficient for most of the underwater applications. Providing a means to amplify and transduce the pressure into an axial load can enhance the pressure sensitivity, as the sensitivity to axial load is considerably larger than that due to hydrostatic loading. The pressure sensitivity of an FBG can be increased by more than an order of magnitude by using a polycarbonate coating [8]. The embedment of the FBG in a polymer filled metal jacket with a small aperture at the end, such that the pressure imposes an axial compression on the fiber, is known to increase the sensitivity by approximately three orders of magnitude, bringing the resolution to 0.02 kPa [9]. A similar scheme, in which the pressure is applied through a hole in the side of the sensor element housing [10] such that the compression of the compliant polymer applies an axial load to the fiber, allows a further order of magnitude improvement in sensitivity.

More recently, many experiments both in macro and micro scale have used cantilever design as the means of transferring load. Using a sensor bonded on top of a cantilever beam increases the area of impact of the wave which in turn increases the pressure sensitivity of the sensor. In this work, the FBG sensor is bonded on a cantilever beam made of Perspex material erected on a rectangular metal frame. The complete assembly of rectangular frame holding the cantilever is positioned inside the Perspex water tank described earlier, which is used to generate and propagate the tsunami wave.

V. RESULTS AND DISCUSSION

A. *Detection of Tsunami Wave Generated from the Deflation of Air bag*

Fig 2 shows a typical time history plot of the strain interpreted from the changes in the centre wavelength of the FBG sensor bonded on the cantilever beam under the influence of the wave pressure. For mimicking a tremor during the seismic activity, the air-bag sandwiched between two metal plates is suddenly deflated. This causes a sudden collapse of the metal plates which in turn produces a transient displacement of water, generating tsunami waves. From the plot it is evident that the envelope of the signal sensed by the FBG sensor characterizes a burst signal generated during the seismic activity under the deep ocean. The maximum strain experienced by the sensor in detecting the generated tsunami is 110 $\mu\varepsilon$, which lies in the sensitivity range of the FBG sensor.

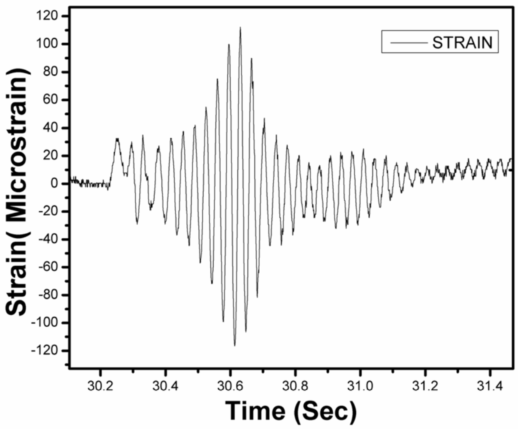

Figure 2. Strain response of an FBG sensor for a tsunami wave generated from an air bag deflation

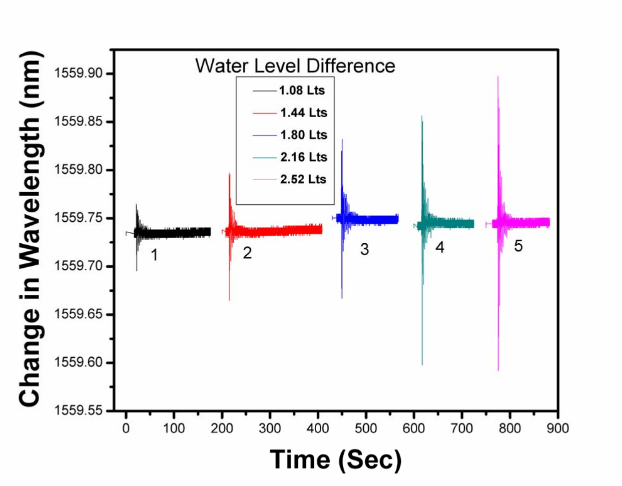

Figure 3.Change in centre wavelength of an FBG sensor for varying water level difference

As FBG sensors have been proved to sense as small as $1\mu\varepsilon$, even the smallest variation of the pressure around the sensor due a weak tremor can be easily sensed. On the other hand FBG sensors have also been experimentally found to withstand as high as 8000 $\mu\varepsilon$, [11] the fragility of this sensor usage for large water pressures can also be ruled out.

B. Detection of Different Pressure Heads Generated by Varying Water Levels Between the Compartments using FBG Sensors

Fig 3 shows the response of a single FBG sensor for varying water pressures. Curves 1 to 5 shows the reaction of the FBG sensor starting from a pressure generated from the water level difference of 1.08 liters to 2.52 liters. FBG sensors in this trial has undergone a minimum wavelength shift of 60 pm and a maximum wavelength shift of 0.17 nm which are well within the sensitivity range [11]. From the plots, it is clear that the change in the central wavelength of the FBG sensor increases with the increase in water level difference.

C. Comparison of FBG Sensor and Digiquartz Sensor Resuts for Varrying Volumes of Water Level Difference

For a new sensor to be accepted in any field, its performance has to be compared and validated against a commercially proven sensor. Simultaneous measurements have been taken from both FBG sensor and the Digiquartz sensor under similar pressure generating conditions placing both the sensor adjacent to each other, inside the tank filled with water.

Fig 4 shows the comparison of wavelength shift of the FBG sensor and the changes in pressure readings of the Digiquartz sensor. The experiments have been conducted with water volume difference of 1.02 litres to 2.52 litres insteps of 0.5 litres to generate tsunami waves of pressure varying from 0.0005 decibar to 0.0040 decibar.

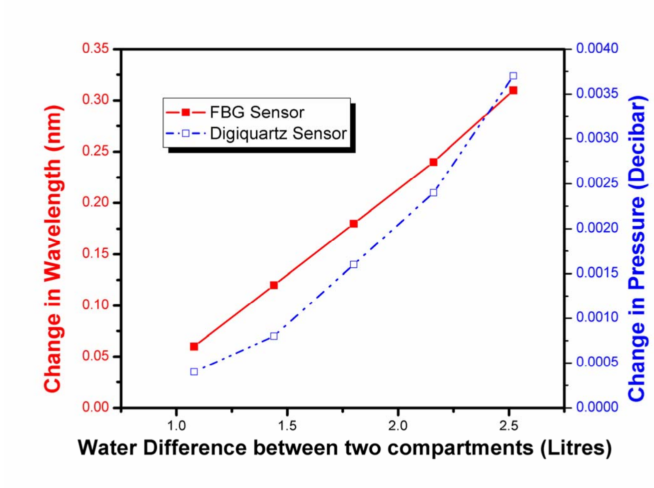

Figure 4. Comparison of FBG and Digiquartz sensor

It can be observed from Fig 4 that the maximum shift in the wavelength of the FBG sensor is 0.325 nm for a pressure variation of 0.00375 decibars which is well within the maximum sensing range of FBG sensor. It is can be observed that the linearity of the FBG sensor response for varying water pressures is better than that of the Digiquartz sensor.

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