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A B S T R A C T

A dual-phase optical fiber-based sensor for early detection against prepreg structural failures is proposed and successfully demonstrated. The sensor consists of an etched fiber Bragg grating (FBG) mounted onto an aluminium plate. The sensor is tested using a simple pressure and petrochemical test rig. By observing the shift of the reflected wavelength of the FBG sensor we can simultaneously detect two parameters: (i) pressure and (ii) petrochemical. The experimental results show the potential of using the FBG sensor for early detection of submarine oil pipe leaking.

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1. Introduction

In recent years, fiber Bragg grating (FBG) optical sensors offer a relatively new technology for the structural monitoring and evaluation of pipeline integrity and performance [1]. The technology is gaining wide acceptance for specific applications in aerospace, maritime and civil engineering structure monitoring, undersea oil exploration, and many other fields [2–5]. The health monitoring of structures and facilities is important in reducing environmental risks and production system failure [6].

The advantages of FBG sensor for strain and temperature measurement in these specific applications over other optical devices are well known (such as embedment in composites, light weight, multi-sensor and explosion-proof). These sensors present an attractive option for applications requiring distributed sensing, real time, and fast response monitoring. In oil and gas industry for example, the use of electrically passive sensor is very important to avoid the risk of fire or explosion [7].

Submerged petroleum/oil pipelines have limited service lifetime and require scheduled maintenance. Pipeline integrity and disturbance are generally not monitored due to lack of any reliable and durable techniques. Cracks in the pipelines will eventually lead to oil leakage. These structural failures are usually dealt with by applying poly-material patches. These patches are called prepreg patches.

Prepreg patches themselves will eventually fail. The current way of determining if a certain patch needs replacing is via visual inspection; usually by means of sending divers under water to manually inspect the presence of oil around the vicinity, or emanating from the patches. As such, the ability to automatically and remotely determine the likelihood of a patch failure leads to cost savings both in terms of maintenance and early leakage prevention.

In this paper, we propose to equip these prepreg patches with a dual-phase optical FBG sensor for early detection against prepreg structural failures. The optical sensor is based on cladding etched Bragg gratings. These sensors can sense the increase in pressure and the change in refractive index on the cladding of the Bragg region simultaneously.

2. Sensing principle

Since the first fiber Bragg grating was demonstrated by K.O. Hill in 1978, FBG has become a very attractive choice for sensing applications. The basic sensing principle commonly used in an FBG based sensor system is by monitoring the shift in the wavelength of the returned (reflected) Bragg signal with respect to the
changes of certain fiber properties, such as modal index or grating pitch [8]. With such a device, injecting a spectrally broad laser will result in a reflected narrowband spectral component at the Bragg wavelength.

In this work, we have designed the FBG sensor in such a way that the first phase of detection involves strain/stress effect. During this phase, depending on how we place the Bragg sensor onto the pipe, the gratings will be subjected to either compression or tension. In the second phase, the presence of the refractive index change, in this case due to the petrochemical, is detected.

For the second phase, we combined fiber Bragg gratings with a wet chemical etch-erosion procedure and demonstrated refractive index sensors. Our approach is using acid hydrofluoric (HF) to remove the cladding layer of the fiber [9]. As the fiber cladding diameter is reduced along the grating region, the effective refractive index is significantly affected by the external refractive index.

![Fig. 1. Aluminium plate design.](image1)

![Fig. 2. (a) Schematic diagram of the experimental setup and (b) composite image of the test rig for the sensor testing.](image2)
The response of a Bragg grating is dictated by the well-known Bragg equation,

\[ \lambda_B = 2n_{eff} \Lambda_B \]  

(1)

where \( \lambda_B \) (nm) is the peak reflected Bragg wavelength, \( n_{eff} \) is the effective refractive index of the waveguide, and \( \Lambda_B \) is the grating period (in nm).

Exposing the outer layer of a waveguide with certain substances such as petrochemical, will alter the effective refractive index of the composite waveguide substance structure. As a result, shifts in the Bragg wavelength combined with the modulation of the reflected amplitude are expected. This approach has already been used to create water level sensors and chemical sensors\(^{[10,11]}\). The beauty of this technique is that it is optical based; hence it is immune to detrimental and hazardous effects such as electromagnetic interference, and reliance on voltage/current (parameters that can lead to unwanted spikes/sparks)\(^{[12]}\).

3. Sensor design

3.1. FBG strain sensor mounting and sample preparation

The FBG sensor consists of three main parts: an aluminium plate which acts as a transducer for the FBG, the etched FBG itself and oil spill prevention paper. The design of the aluminium plate is shown in Fig. 1.

It is necessary to develop a suitable encapsulation or mounting technique for the FBG sensor\(^{[13]}\). For this purpose, an aluminium plate measuring 140 mm long \( \times \) 30 mm wide \( \times \) 1.5 mm thick was designed and fabricated. A number of FBG sensors were prepared and mounted along the long axis of the plate.

The peak reflectivity values for our FBG are typically 90% and located around 1550 nm. The physical grating lengths are set to 2 cm long for all samples. A solution with 48% hydrofluoric (HF) acid was used to etch the cladding layer of the optical fiber. The etched FBGs are then mounted onto the aluminium plate by gluing both ends of the grating using UV cured Norland Optical Adhesives (NOA 61).

The experimental setup for measuring the Bragg wavelength shift is shown in Fig. 2(a). A broadband source in the form of amplified spontaneous emission (ASE) from an erbium doped fiber amplifier module was used. The spectral power of the ASE source is around 100 mW. The input signal passes through a circulator before being reflected by the Bragg sensor and directed to an optical spectrum analyser. The sensor assembly (FBG mounted onto an aluminium plate) was clamped at both ends of the pipe. The length of the pipe is 350 mm and its diameter is 50.8 mm (2 in.). A punched rubber patch located between the two FBG sensors allows petrochemical to emanate and this is used to indicate that the prepreg is damaged. A photo of the implemented experimental setup is depicted in Fig. 2(b). The FBG wavelength shift was continuously monitored every minute for 1 h. The Bragg wavelength of this sensor system was then recorded and processed using LabVIEW software.

![Fig. 3. Response of Bragg wavelengths shift upon exposure to petrochemical.](image)

![Fig. 4. Bragg wavelength shift against pressure influence.](image)

![Fig. 5. (a) Normalized Bragg wavelength shift with exposure to petrochemical under pressure influence and (b) normalized Bragg wavelength shift with exposure to petrochemical under pressure influence, with the assembly submerged in water.](image)
The sensor was tested under two conditions (i) Bragg gratings embedded patch under controlled conditions and (ii) dynamic conditions (submerged in water). The sensor is covered by the oil spill paper in order to maximize the surface contact between the leaked oil and the sensor. The oil spill paper is water resistant and will only absorb oil.

4. Results and discussion

The first phase of this work is to calibrate the Bragg sensor's response to petrochemical exposure. This was done by filling petrochemical into the pipe and allowing it to leak out of the hole in the rubber patch. The Bragg peak wavelength shift is then continuously recorded.

Fig. 3 shows the temporal dependence of the resonant Bragg wavelength of the grating under the petrochemical influence for 120 min. The reflection spectrum shifts to longer wavelength ranges due to the change of index of the surrounding medium around the core of the grating sensor. The increase is not linear because the petrochemical was made to leak just for an instant and then drying commences immediately. After 60 min, the petrochemical was removed from the pipe and the oil spill paper is left to dry. A maximum Bragg wavelength shift of 0.25 nm was recorded and this wavelength shift slowly returns to the initial Bragg wavelength in the subsequent 60 min.

Fig. 4 shows the relationship between the average Bragg wavelength shifts, \( \Delta \lambda \) (nm) and applied pressure. The inset in Fig. 4 shows the inflated rubber patch acting like a damaged preprep, resulting in a significant axial strain on the fiber. This can be easily measured through the negative shift of the grating Bragg wavelength. As seen in Fig. 4, the strain responses are exponential with pressure, which is considered abnormal for FBG strain sensors. The maximum wavelength shift recorded is \(-1.85\) nm. After that, the wavelength shift became saturated due to the maximum compression of the grating zone.

The second phase of the work involves subjecting the patch with petrochemical and pressure simultaneously. The experiment was performed repeatedly in a controlled laboratory environment where the timing and the extent of the petrochemical leak were controlled manually. The experiment was followed by investigating cases where the pipe was submerged in water.

Fig. 5(a) shows the normalized wavelength shift with exposure to both petrochemical and pressure, while Fig. 5(b) shows the response of the normalized Bragg wavelength shifts when the assembly is submerged in water. As can be seen from Fig. 5, as we increase the pressure in the pipe, the normalized wavelength shift moves towards the negative shift wavelength. This indicates that when there is increased rubber inflation due to pressure, the grating zone compresses. At a certain point, when the pressure in the pipe increases, the normalized wavelength shift starts to shift to positive value.

This indicates that the leaked petrochemical has come into contact with the FBG sensor, and the reflected wavelength shift is due to the changes in the effective refractive index of the FBG. As shown in Fig. 5, both sensors in different conditions share the same pressure variation trend. However, the reaction with the petrochemical sensor is more significant when the assembly is submerged in water, as compared to the normal conditions. This is possibly due to water assisting in transport of the petrochemical.

Using this sensor, we can detect two parameters—pressure and petrochemical simultaneously. We can clearly see when the preprep is broken as this causes oil leak. By observing the shift of the reflected wavelength, we can monitor the condition of the preprep remotely and decide whether the pipe should be replaced or otherwise. Since the sensed information, namely the petrochemical leakage, is wavelength-encoded, it is independent from signal fluctuations due to light sources, connectors or fiber losses. Another point which is crucial in a hazardous environment is the feasibility of remote sensing. This is because commercial fibers have low losses in the operating wavelength range used in this work and are able to transmit the sensed information to distant monitoring locations.

In addition, the narrow bandwidth of the FBG allows multiplexing of many sensing elements with known Bragg wavelengths, at predetermined positions along the length of the pipeline or tank design. Each sensor can work independently without interfering with one another, thereby providing distributed sensing of both leakages at their respective locations.

5. Conclusion

We have successfully developed and demonstrated experimentally a dual-phase optical-based interrogator for use as an early detection system against structural failure and cracks on preprep patches. The sensor consists of an etched FBG attached onto an aluminium plate. It is able to detect pressure and petrochemical simultaneously. The inflating rubber acts like a damaged preprep, resulting in a significant axial strain of fiber and this can be easily measured from the negative shift of the Bragg grating wavelength. Positive shift of the Bragg wavelength occurs when oil starts to leak from the pipe. This approach offers an efficient, fast, safe and inexpensive technique for applications involving remote monitoring of leakages in petrochemical pipelines.

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References

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