STRAIN-INSENSITIVE FIBER BRAGG GRATING ULTRASONIC SENSING SYSTEM USING FIBER RING LASER

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1 Introduction

Damages in composites, such as matrix cracks, delamination and fiber breakage, may occur as a result of excessive load, fatigue and low-velocity impact, etc. These damages can be inspected by ultrasonic testing. Conventionally, piezoelectric sensors have been employed as transducers and sensors in ultrasonic testing. Recently, fiber Bragg gratings (FBGs) are expected to provide a replacement for traditional piezoelectric ultrasonic sensors, because FBGs are easy to be embedded into composite structures, not susceptible to electromagnetic field, and enable multiplexing [1].
Previously reported FBG ultrasound sensing systems can be classified into two types in terms of light source employed, *i.e.*, laser and broadband light [2]. A system employing a laser where the lasing wavelength is tuned to 50% reflectivity of the FBG permits sensitive ultrasonic detection. However, the ultrasound sensitivity wanes with the change in strain applied to an FBG because strain causes shift in the FBG reflection spectrum. A system with broadband light source incorporating two Fabry-Perot filters can detect ultrasound regardless of strain applied to an FBG. However, the ultrasound sensitivity periodically depends on the Bragg wavelength of the FBG sensor and the system is lack of ultrasonic sensitivity to detect acoustic emissions [3].
This paper presents a novel FBG ultrasound sensing system using a fiber ring laser. Ultrasound detection of this system proved to be insensitive to strain applied to the FBG sensor. Furthermore, this system was applied to detect low-frequency vibration. Experimental results demonstrated that this system could detect low-frequency vibrations by low-pass-filtering the FBG sensor signal.

2 Ultrasound detection

2.1 Fiber ring laser system

An optical setup shown in Fig. 1 was used to detect ultrasound. This system includes a fiber ring laser consisting of an FBG, an optical circulator, a bi-directional optical coupler and an optical amplifier. A semiconductor optical amplifier was used as an optical amplifier in this study. The working principle of the system shown in Fig. 1 is as follows. An optical amplifier has two functions: weak broadband light emission, and amplification of optical power having relatively high intensity. A weak broadband light emitted from an optical amplifier travels to an FBG and the FBG reflects a narrow band light at the Bragg wavelength. Small part of narrowband light travels into a photodetector where the intensity of light is converted into a voltage signal. Remaining almost light reflected from the FBG is transmitted to the optical amplifier where the intensity of narrowband light is boosted. Then the amplified narrowband light travels to the FBG and it reflects a narrow band light at the Bragg wavelength again. These processes are repeated in the fiber ring cavity at the speed of light. As such, this arrangement ensures that lasing occurs at the Bragg wavelength

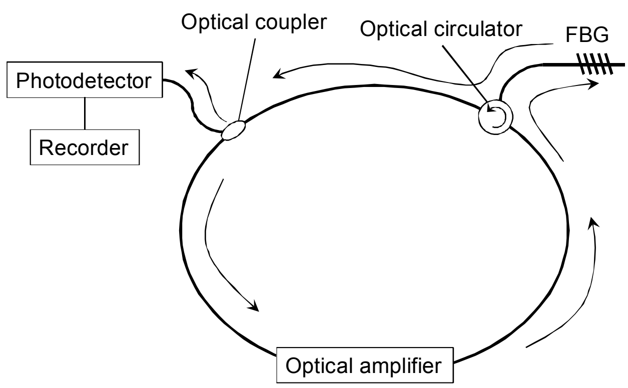

Fig.1. An FBG ultrasonic sensing system.

of the FBG.

2.2 Working principle of ultrasound detection

The optical gain of an optical amplifier depends on wavelength. Ultrasound impinging on an FBG results in a minute shift (less than 1 pm) in the Bragg wavelength at which lasing occurs [4]. As a result, the intensity of laser generated from a fiber ring laser varies in accordance with ultrasonic vibration exerting on the FBG. The ultrasound sensitivity of the system is attributed to wavelength dependence of the optical gain in an optical amplifier. The intensity of laser can be measured from a photodetector to which part of laser light is transmitted [5].

The optical gain depends on wavelength in the whole operating wavelength range of an optical amplifier. Therefore, this system is considered to be capable of detecting ultrasound regardless of the Bragg wavelength of the FBG sensor, *i.e.*, the system can detect ultrasound regardless of strain applied to the FBG sensor.

2.3 Ultrasound detection using a fiber ring laser system

A 10-mm-long FBG with a Bragg wavelength of 1550 nm was bonded on a 1-mm-thick cross-ply CFRP plate and the response to ultrasound propagating on the CFRP plate was recorded. Ultrasound was generated from a piezoelectric ultrasound transmitter whose central wavelength was 250 kHz. The transmitter was put on the CFRP plate 100 mm away from the FBG sensor.

Fig. 2 (a) and (b) show the FBG sensor responses to individual ultrasound pulse excited by a 3-cycle toneburst signal of a frequency of 250 kHz and an impulse signal, respectively. As can be seen from these well-defined responses to individual ultrasound, this system possesses ultrasound sensitivity enough to apply ultrasonic inspection and acoustic emission measurement.

2.4 Ultrasound detection under varying strain condition

Ultrasonic responses of an FBG sensor subjected to various strains were recorded using the same experimental setup employed in the previous section. A resistive strain gauge was attached next to the FBG sensor to serve as a strain reference. Ultrasound was excited by a 3-cycle toneburst signal at a frequency of 250 kHz in this experiment.

Fig. 3 (a), (b) and (c) show the ultrasonic responses of an FBG sensor subjected to -600 με, 0 με and 600 με, respectively. A well-defined ultrasound response was obtained regardless of strain applied to the FBG sensor. Furthermore, the ultrasonic sensitivity seems to be independent of strain applied to the FBG sensor.

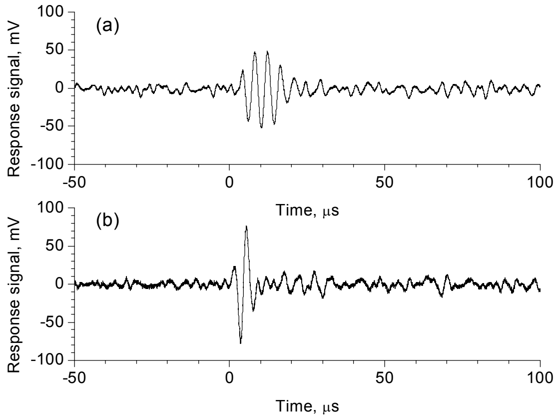

Fig.2. FBG sensor responses to an individual ultrasound pulse propagating on a cross-ply CFRP plate. Ultrasound excited by (a) a 3-cycle toneburst signal, (b) an impulse signal.

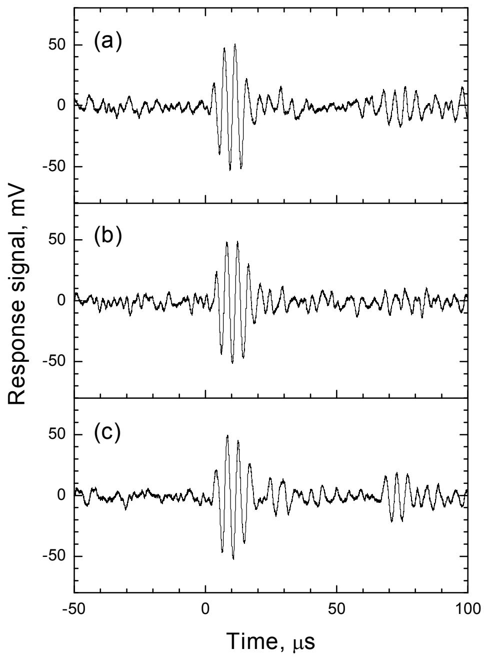

Fig.3. Ultrasonic responses of an FBG sensor subjected to various strain. Strain (a) at -600 με, (b) strain-free, (c) at 600 με.

Fig. 4 shows the shift in reflection spectrum of the FBG sensor subjected from -600 με to 600 με. The strain change shifted the Bragg wavelength by 1.47 nm. This system could detect ultrasound despite considerable shift in the Bragg wavelength. These experiments proved that this system was capable of detecting ultrasound regardless of strain applied to the FBG sensor.

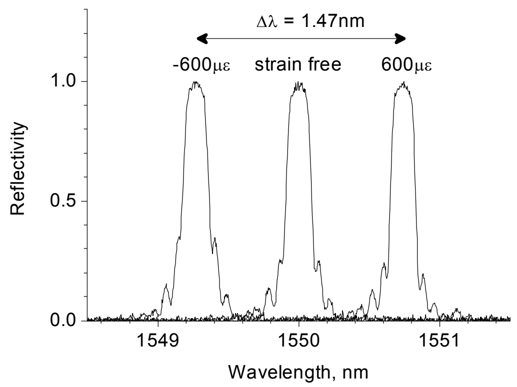

Fig.4. Shift in reflection spectrum of an FBG sensor in which strain ranged from -600 με to 600 με.

3 Vibration detection

3.1 Experimental setup

The FBG sensor response of the fiber ring laser system to mechanical vibration was investigated. An experimental setup shown in Fig. 5 was used in the test. A 10-mm-long FBG sensor with a Bragg wavelength of 1550 nm, a resistive strain gauge and a piezoelectric ultrasonic sensor were bonded to a 500 × 50 × 1 mm^3 cantilevered cross-ply CFRP plate. A mechanical vibration was given by dropping a 2.7-gram ceramic ball from a height of 300 mm. The impact point was 200 mm away from the point where the FBG sensor was bonded. Responses of attached sensors were recorded before and after a dropping ball impact.

3.2 Experimental results

Fig. 6 shows a 50-kHz-low-pass-filtered FBG sensor response to impact along with a piezoelectric sensor response. Both sensors had a significant response to the impact and obvious responses continued for around 15 milliseconds after impact.

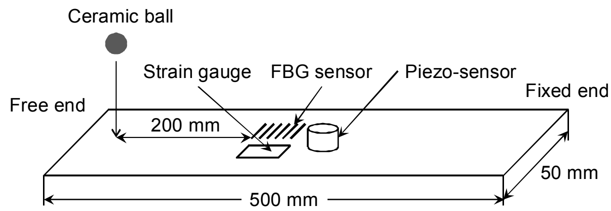

Fig.5. Experimental setup for detecting an impact by dropping ball.

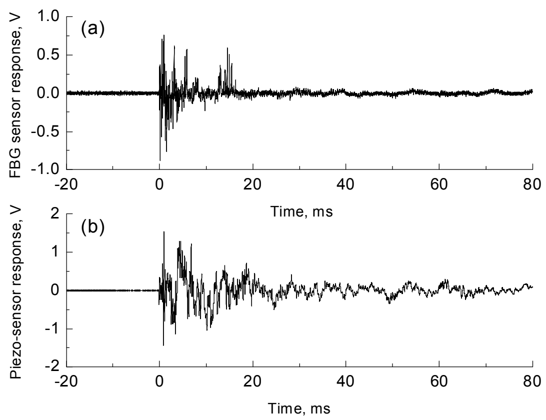

Fig.6. Responses to a dropping ball impact. (a) 50-kHz-low-pass-filtered FBG sensor response and (b) piezoelectric sensor response.

Fig. 7 (a) and (b) depict a 100-Hz-low-pass filtered FBG sensor response and strain curve measured with a strain gauge, respectively. Both sensor responses showed a similar damped vibration behavior after impact. Frequency domain representations of the FBG sensor response and strain curve are shown in Fig. 8 (a) and (b), respectively. The frequency having the maximum component intensity of the FBG sensor response was 4.9 Hz which agreed with vibration period of the cantilever beam.

As shown in Fig. 6, the FBG sensor of this system responded to an impact as a high-frequency signal which is similar to a piezoelectric sensor. Furthermore, the FBG sensor detected a low-frequency vibration which corresponded to strain measurement with a resistive strain gauge. These experiments demonstrated that the fiber ring laser system could detect not only ultrasound but also impact and low-frequency vibration through an appropriate low-pass filter process of the FBG sensor signal.

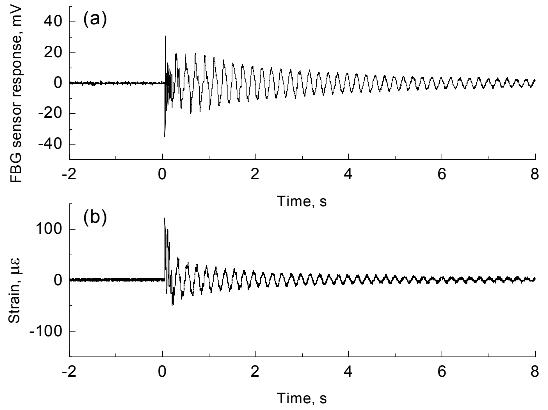

Fig.7. Vibration curve of a cantilever beam, as measured with (a) FBG sensor and (b) resistive strain gauge.

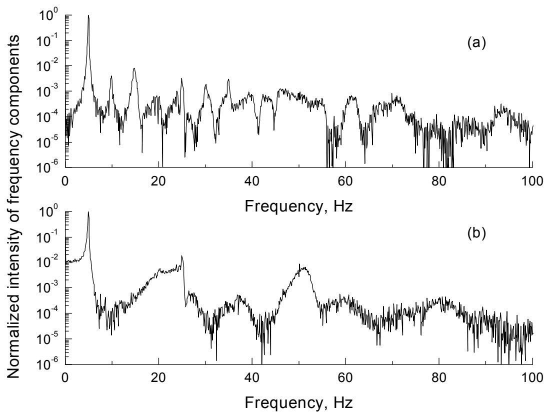

Fig.8. Frequency domain representation of vibration curve obtained from (a) FBG sensor and (b) resistive strain gauge.

4 Conclusions

An FBG ultrasonic sensing system incorporating a fiber ring laser was constructed. The fiber ring laser lased at the Bragg wavelength of the FBG sensor and the system proved to be capable of detecting ultrasound regardless of strain applied to the FBG sensor. The application of this system is not limited to ultrasound detection; this system could sense vibration over a broadband, ranging from mechanical vibration at a frequency of a few Hz to ultrasound more than 100 kHz. In spite of its simple configuration, this system has a high sensitivity to vibration and seems to be suited to structural health monitoring under varying strain condition.

Acknowledgements

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