Development of fiber optic broadband vibration-detection system

— Simultaneous measurement of both strain and acoustic emission using a fiber Bragg grating sensor —

Hiroshi TSUDA*, Eiichi SATO, Tomio NAKAJIMA and Akiyoshi SATO

[Translation from *Synthesiology*, Vol.6, No.1, p.45-54 (2013)]

Structural integrity can be examined using methods that evaluate response to vibration, such as hammering tests and ultrasonic inspections. Fiber optic sensors are expected to allow structural health monitoring in harsh environments where conventional electric sensors cannot be used. Recently, detection of vibration with a fiber Bragg grating (FBG) has been intensively investigated, because FBGs have many advantages such as multifunction abilities, multiplexing, and electromagnetic immunity. In using previously proposed systems incorporating FBGs, however, there was a technical difficulty in detecting ultrasound under varying temperatures and strain conditions. We developed a novel system that overcomes this technical barrier. Our system is also capable of detecting vibrations across a broad frequency band from several Hz to around 2 MHz. This paper presents how our compact and economical vibration-detection system with an FBG sensor was developed.

Keywords : Ultrasound, vibration, acoustic emission, non-destructive testing, fiber-optic sensor

1 Introduction

The presence of defects in structures can be inspected with a test utilizing vibrations, such as a hammering test or an ultrasonic test. Acoustic emission (AE) measurements can monitor the integrity of materials and structures because the initiation of a crack generates AEs whose frequencies range from tens of kHz to hundreds of kHz. In rotating machines, it is known that the misalignment of a rotary shaft and the failure in a ball bearing give arise to anomalies in vibrations in which high intensity components appear in a frequency range different than the rotary frequency.[1] Thus, vibration measurement plays an important role in monitoring the health of structures and machinery.

Electric sensors such as resistive strain gauges and piezoelectric sensors are conventionally used in vibration measurement. Strain gauges are used to measure vibrations up to a frequency of several kHz, and piezoelectric sensors are used to measure vibrations at higher frequency. Piezoelectric sensors are selectively used to cover the frequency range to be monitored because of their resonant characteristics, i.e., narrowband frequency response characteristics. In other words, there is no electric sensor capable of detecting vibration in a wide frequency range from mechanical vibration to ultrasound. Therefore, the development of a broadband sensor and its measurement system can enhance the convenience of a non-destructive inspection test utilizing vibrations.

There are a growing number of structures to which the application of electric sensors is unsuitable. Carbon fiber-reinforced plastics (CFRPs) are widely applied to structural members of cars, airplanes and turbine blades of wind power generation because CFRPs have the advantages of high specific strength and rigidity, and a great amount of flexibility when used in structural design. Electrically conductive CFRP structures, however, are prone to being hit by lightning. The application of electric sensors to CFRP structures is inappropriate because lightning would damage the installed electric sensors. In addition, electric sensors decay in a long term application. No electric sensor can withstand the application of structural health monitoring over decades, such as those at a radioactive waste storage facility.

A fiber optic sensor can solve these challenges of electric sensors. Among the variety of fiber optic sensors, a fiber Bragg grating (FBG), which is a wavelength-modulation fiber optic sensor, is a promising candidate for sensors in structural health monitoring because of its multifunctionality and multiplexibility. Thus far, many FBGs have been used as sensors for measuring strain and temperature. There have been extensive studies on the detection of ultrasound and AE using an FBG recently.[2] There is a large technical barrier, however, to detect AE using an FBG, as mentioned below. Table 1 shows the features of sensors for detecting vibrations.

This paper reports the development of an FBG sensor system that is capable of measuring strain and detecting

Research Institute of Instrumentation Frontier, AIST Tsukuba Central 2, 1-1-1 Umezono, Tsukuba 305-8568, Japan
* E-mail: hiroshi-tsuda@aist.go.jp

Original manuscript received June 18, 2012, Revisions received August 30, 2012, Accepted September 10, 20102

Table 1. Features of vibration sensors

	Strain gauge	Piezoelectric sensor	FBG sensor
Response frequency range	up to a few kHz	tens of kHz ~ tens of MHz	a few Hz ~ 2 MHz
Strain measurement	○	×	○
ultrasound・AE measurement	×	○(*1)	○(*2)
Simultaneous measurement of both strain and AE	×	×	○
Durability	×	×	○(*3)
Electromagnetic interference	×	×	○
Unit price (JPY)	300 ~ 600	3,000 ~ 300,000	10,000 ~ 30,000

(*1) An appropriate piezoelectric sensor should be chosen in accordance with the frequency range to be measured.
(*2) There is a large technical barrier in existing technology for measuring AE with an FBG sensor.
(*3) There are time limitations in the application of an FBG sensor at a high temperature of more than 400 degrees C or in strongly radioactive environments where the FBG is eliminated.

AE simultaneously. The system was developed through collaborative research among the Japan Aerospace Exploration Agency (JAXA), two private companies and the National Institute of Advanced Industrial Science and Technology (AIST).

2 Expectations of an FBG sensor system for structural health monitoring

Recently, parts of airplanes have been manufactured based on a damage-tolerant design that predicts the structural lifetime on the assumption that crack propagation until the point of an allowable crack length can be tolerated. Such structures based on a damage-tolerant design concept require an inspection that detects a crack before reaching the allowable length. The structural reliability can be remarkably improved if the occurrence and propagation of cracks are monitored during use.[3] Thus, a smart structure including a self-diagnosing system, e.g., a function to measure strain and AE, has been given much attention in aerospace research. The development of a structural health monitoring system incorporating a simple and durable sensor network is essential for realizing smart structures.

Strain and AE are conventionally measured with a strain gauge and a piezoelectric sensor, respectively, which are electric sensors. The electric sensor network for a large-scale structure would be complex and cumbersome because electric cables are required for these sensors. In contrast, FBGs are suitable sensors for a smart structure because FBGs are lightweight and can offer a simple sensor network in which several FBGs are installed on a single optical fiber through a wavelength-division multiplexing (WDM) technique. Thus, an FBG sensor system capable of measuring both strain and AE is considered a core technology for smart structures.[4]

3 Fiber Bragg gratings

3.1 Ultrasonic detection using an FBG

An FBG consists of periodical refractive index modulation in the core of an optical fiber. When light passes through an FBG, the FBG reflects narrowband light whose central wavelength is called the Bragg wavelength.[5] The Bragg wavelength shifts with the strain and temperature applied to the FBG. An FBG whose Bragg wavelength is 1550 nm has sensitivities to strain and temperature of 1.2 pm/$\mu\varepsilon$ and 14 pm/K, respectively. An FBG is employed as a strain or temperature sensor by measuring the Bragg wavelength with an optical instrument such as an optical spectrum analyzer or a wavelength-meter. FBGs have excellent durability except under high temperatures, exceeding 400 degrees C, or in strong radioactive environments. The application of FBG sensors in such harsh environments is subject to a time limitation because the refractive index modulation of an FBG disappears upon exposure. The time limitation in usage must be considered when using FBG sensors in harsh environment, such as a radioactive waste storage facility.

A dynamic Bragg wavelength shift induced by impact vibration cannot be detected from a reading of the Bragg wavelength using an optical measurement instrument such as a wavelength-meter because the sampling rate is a few Hz at most. A fast Bragg wavelength shift arising from ultrasonic vibration can be detected using the following two systems.[6][7] One is an optical filter demodulation system. The light reflected from a broadband light-illuminated FBG is sent to an optical filter whose optical characteristics vary with wavelength. The intensity of light transmitted through or reflected from the optical filter varies with the vibration of ultrasound impinging on the FBG sensor. The other is a laser demodulation system in which a laser is tuned to a wavelength where the gradient of the FBG reflection spectrum is steep. Usually, the laser wavelength is set to 50 % of the reflectivity. A laser demodulation system allows highly sensitive ultrasonic detection by measuring the intensity of light reflected from the FBG.

3.2 Technical barrier of AE detection with an FBG

AEs accompanied by a microscopic failure occur when a material is exposed to strain or a change in temperature. Therefore, an AE measurement system must be capable of detecting ultrasound under varying strain and temperature conditions. AE exerted on an FBG shifts the Bragg wavelength a few picometers because AE causes a strain oscillation of a few $\mu\varepsilon$ at most.[8] Such a subtle and fast Bragg wavelength shift can be detected sensitively with a laser demodulation system. However, as shown in Fig. 1, the Bragg wavelength shifts by 0.1 nm when the FBG is subjected to a strain of 0.008 % or temperature change of 7 K. The lasing wavelength deviates from the operating range by such a small change in strain and temperature. Thus, it is difficult for a laser demodulation system to detect AE continuously under varying strain and temperature conditions. An optical filter demodulation system is unlikely to detect AE sensitively due to its poor ultrasonic sensitivity. As mentioned above, the technique for detecting AE with an FBG is not well established. The development of a FBG sensor system capable of detecting ultrasound under varying strain and temperature conditions is awaited.

4 Development of an AE measurement system employing an FBG

The authors had joined a JAXA Space Open Lab project named “R&D of technology for monitoring the health of large-scale structures” from the autumn of 2008 until the spring of 2011. There were two goals for this research project. The first is to develop an FBG sensor AE measurement system that can be installed on space structures such as a rocket. The second is to construct an FBG sensor system featuring simultaneous multi-point measurements of both strain and AE. In the research project, AIST was in charge of developing the measurement technique. Two companies were in charge of designing and manufacturing the measurement systems and conducting experiments. JAXA was in charge of providing verification tests and administering the research project.

In 2008, when the research project commenced, an optical filter demodulation system incorporating an optical filter with periodical optical characteristics such as an arrayed waveguide grating (AWG) and a Fabry-Perot filter seemed to show potential for detecting AE.[9][10] The AE detectability of an FBG was unknown because there had been no reports on AE measurements with an FBG sensor. In the first year of the project, we concentrated on the following two tasks. One is to evaluate the AE detectability of an FBG sensor. The other is to confirm the possibility of AE measurement using an optical filter demodulation system.

4.1 AE measurement by a laser demodulation technique

AEs of a CFRP pressure vessel used for a rocket motor case during a pressure proof test are detected with a strain-insensitive FBG sensor incorporated in a laser demodulation system. The AE detectability of an FBG is compared with that of a piezoelectric sensor conventionally used in AE detection. In the previously reported ultrasonic measurement using a laser demodulation system, an FBG was glued on or embedded in the structure to be tested, as shown in Fig. 2(a). The reflection spectrum of the FBG installed in such a manner shifts with the strain applied to the test structure. AE that occurs continuously under varying strain conditions might be detected by tuning the lasing wavelength in accordance with the reflection spectrum shift. However, the tuning of the lasing wavelength cannot follow a sudden discontinuous strain change arising from a substantial failure in the test structure.

In this study, part of an FBG inscribed-optical fiber other than the grating section is bonded to the test structure to isolate the FBG from the strain applied to the test structure, as shown in Fig. 2(b). AEs occurring in the test structure travel through the optical fiber via the point of contact between the structure and the optical fiber and eventually impinge on the grating. The change in temperature can be negligible in an indoor experiment. This sensor arrangement permits a continuous AE measurement under varying strain conditions.

Figure 3 shows the cumulative AE hit curves detected from an FBG and a piezoelectric sensor, with the pressure-time curve. Both sensors begin to detect AE from a pressure exceeding 1 MPa. The AE curves of both sensors show similar behavior throughout the test. The experiment demonstrated that an FBG had ability to detect AE comparable to a piezoelectric sensor.[11]

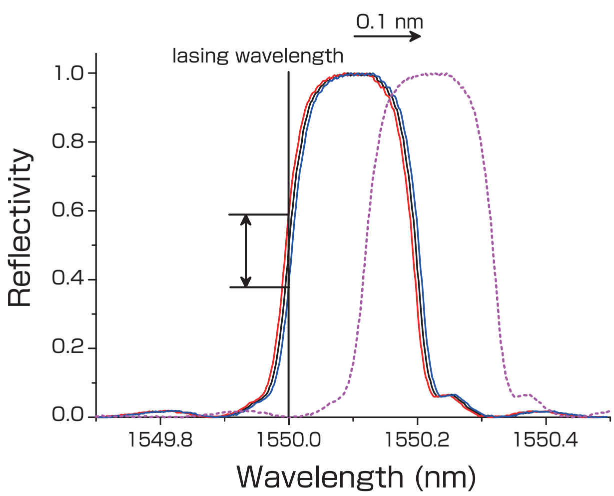

Fig. 1 Ultrasonic detection based on a laser demodulation
The reflective spectrum shifts by 0.1 nm when an FBG is exposed to a strain of 0.008 % or a change in temperature of 7 K.

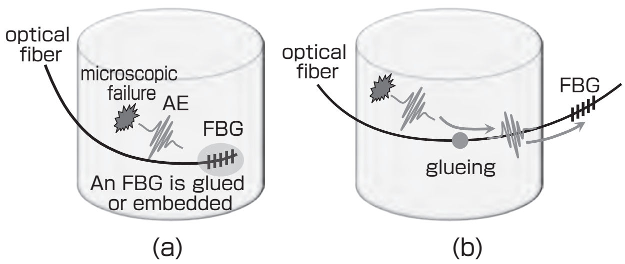

Fig. 2 FBG sensor installation onto a structure to be monitored
(a) conventional installation, (b) strain-insensitive installation.

4.2 AE measurement by an optical filter demodulation technique

There are limitations in size, weight and power consumption in a system installed in a space structure. JAXA presented the following specifications of an AE measurement system for a space structure: smaller than 200 × 300 × 150 mm^3 in size, less than 4 kg in weight and less than 14 W in power consumption. A laser demodulation system cannot meet the specifications mentioned-above because it consists of large and heavy measurement instruments such as a tunable laser and an optical spectrum analyzer.

An optical filter demodulation system can meet the specifications in spite of the lower AE sensitivity. According to a previous study on ultrasonic detection using an optical filter demodulation system, ultrasound sensitivity can be maximized by using an optical filter whose free spectral range (FSR) corresponds to the spectral width of an FBG reflection spectrum.[10] Two types of an optical filter for the demodulation are available: an AWG and a Fabry-Perot filter. A commercially available Fabry-Perot filter provides a variety of FSR, although there is little choice of FSR in AWG. Thus, an optical filter demodulation system including a Fabry-Perot filter was constructed and applied to the AE measurement of CFRP.

Although the optical filter demodulation system met the specifications for installation into a rocket, it was difficult to distinguish between AE and background noise due to the low AE sensitivity. The intensity of light reflected from an FBG incorporated in the optical filter demodulation system was as feeble as 0.01 % of that obtained from a laser demodulation system. The improvement in the AE sensitivity of the optical filter demodulation system that utilizes such feeble light seemed to be difficult. There was no prospect to develop an AE measurement system for a space structure at the end of the first year of the research project.

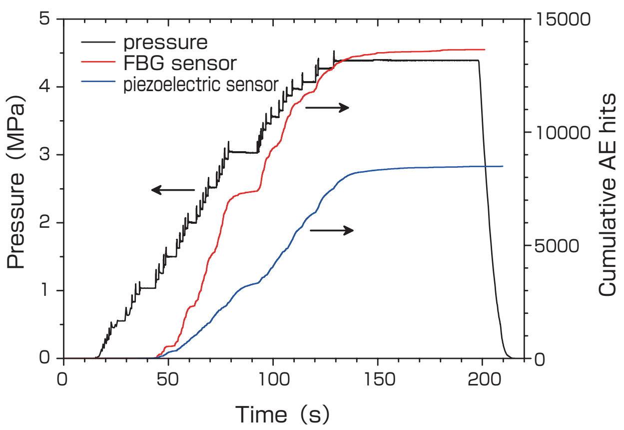

Fig. 3 Pressure and cumulative number of AE hits plotted with respect to time during the pressure test of a CFRP vessel

4.3 Development of a novel AE measurement system using a fiber ring laser

The influence of a grating length of an FBG sensor on the ultrasonic sensitivity was investigated at the end of the first year of the research project. The setup of a laser demodulation system used in the experiment is shown in Fig. 4. The laser wavelength appropriate for ultrasonic detection always fluctuates because a tiny change in strain and temperature shifts the reflection spectrum. In the experiment, ultrasound was detected in the following procedure. First, set the optical switch of the system to Port 1 and measure the reflection spectrum of a broadband light-illuminated FBG with an optical spectrum analyzer. Second, turn the optical switch to Port 2 and tune the lasing wavelength at 50 % of the reflectivity of the FBG sensor. Then, the ultrasound is detected as the photodetector output.

In some cases, the ultrasound was barely detected by averaging the ultrasonic responses in spite of using a laser demodulation system featuring a high sensitivity to ultrasound. The reduction in ultrasonic sensitivity was found to result from an operational error, where the optical switch was not turned to Port 2 when detecting the ultrasound. This operational error, however, demonstrated that ultrasound could be detected from a broadband light-illuminated FBG without an optical filter for demodulation. Ultrasound oscillates the reflection spectrum of an FBG within a range of a few picometers. This ultrasound detection must utilize a slight wavelength dependence of optical power emitted from the light source because a tiny oscillation of the reflection spectrum is detected as a change in the intensity of the light.[12] The utilization of the wavelength dependence of optical power was a new idea in demodulating ultrasounds. The authors expected that this demodulation could lead to a breakthrough in the development of a novel compact FBG sensor system because it did not need a demodulating optical filter.

Let us consider the improvement in ultrasonic sensitivity using the wavelength dependence of the optical power. The optical power spectrum of the broadband light source used in the experiment is shown in Fig. 5(a). The optical power tends to decrease slightly with wavelength at approximately 1550 nm, at which the FBG used in the experiment has the Bragg wavelength. The optical power spectrum at approximately

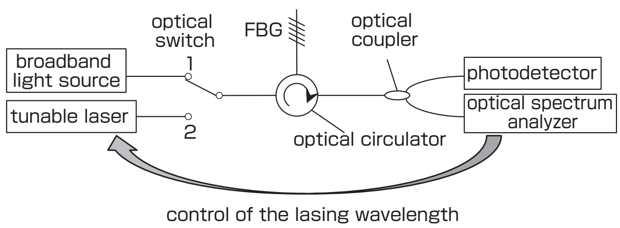

Fig. 4 A setup of a laser demodulation system

1550 nm is schematically shown in Fig. 5(b). The optical power is assumed to vary from 0.5 to 1 by ultrasonic vibration. If the intensity of light reflected from FBG is 10, ultrasound vibration causes a variation in the optical power ranging from 5 to 10. If the intensity of light reflected from an FBG increases to 100, the identical ultrasonic vibration gives rise to a change in the optical power of 50. Thus, ultrasound sensitivity can be improved by intensifying the power of light reflected from the FBG. The usage of a high power broadband light source or a fiber ring laser can intensify the light reflected from the FBG. However, a system employing a high power broadband light source is inefficient because it only utilizes a fraction of power emitted from the light source. Consequently, a system including a fiber ring laser was constructed.[13]

A setup of a fiber ring laser is shown in Fig. 6. A fiber ring laser consists of an optical amplifier, an optical circulator, an optical coupler, an FBG, a photodetector and optical fibers connecting these optical components. An optical amplifier both emits weak broadband light and amplifies wavelength components with relatively high intensity. The weak broadband light emitted from the optical amplifier reaches an FBG through an optical circulator. The narrowband light at the Bragg wavelength is reflected from the FBG and is propagated along the looped optical fiber. The light is separated into two directions at the optical coupler. Part of the light goes to a photodetector, where the intensity of light is converted into a voltage signal. The remaining light goes back to the optical amplifier, where the Bragg wavelength light is boosted. This system emits a laser at the Bragg wavelength of the FBG because the light at the Bragg wavelength is repeatedly amplified by being circulated through the looped optical fiber. If the ring cavity of the system consists of a 10-meter-long optical fiber, the time required for the light reflected from the FBG to circulate the ring cavity is approximately 33 ns, which corresponds to 30 MHz in frequency. The fiber ring laser emits a laser at the Bragg wavelength corresponding to strain and temperature applied to the FBG at a sufficient response speed. The intensity of the laser is modulated by the Bragg wavelength of the FBG by utilizing the wavelength dependence of the gain of the optical amplifier incorporated in the fiber ring laser. Although the Bragg wavelength shift induced by the ultrasound is only a few picometers at most, the fiber ring laser system converts such a subtle shift to a measurable change in the laser intensity because of the high intensity of the laser.

A technique to measure the wavelength of a laser emitted from a fiber ring laser using an optical instrument is commonly used to evaluate strain and temperature. However, the technique to detect vibration impinging on an FBG by utilizing a wavelength dependence of optical gain of an optical amplifier incorporated in a fiber ring laser is a unique invention of the present study.

An example of ultrasound detection using a fiber ring laser system is shown here. Figure 7 shows the wavelength shift in a reflection spectrum of an FBG glued on a CFRP plate that undergoes a strain change of ±0.06 %. In the case of a laser demodulation, the laser wavelength must be tuned in accordance with the shift of the reflection spectrum. In contrast, a fiber ring laser spontaneously emits a laser at the Bragg wavelength of the FBG sensor regardless of the shift in the reflection spectrum. A fiber ring laser system could detect ultrasound irrespective of considerable shift in the Bragg wavelength, as shown in Fig. 8.[14]

A fiber ring laser system was found to respond to vibration in a broadband range from a few Hz to 2 MHz. As shown in Fig. 9, a fiber ring laser-based AE measurement system that met the specification for the installation into a rocket structure and had sufficient AE sensitivity to monitor the microscopic fracture of CFRP was assembled in the spring of 2010.

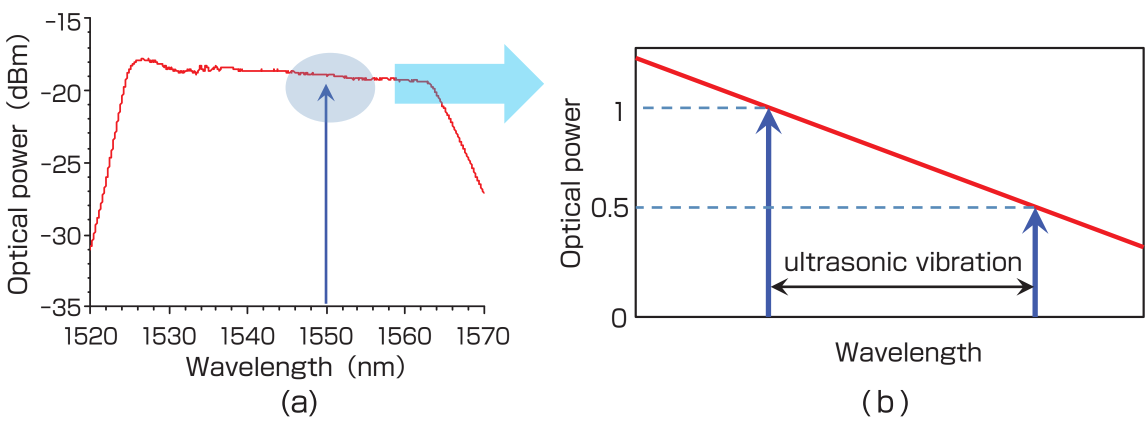

Fig. 5 (a) Optical power spectrum of the broadband light source employed, (b) a schematic illustrating the optical power distribution at approximately 1550 nm

5 Development of a simultaneous multi-point measuring system of both strain and AE

The final target of our research project was to develop a system that can simultaneously measure strain up to 1 % and AE using four FBG sensors. To measure strain and AE simultaneously, the output of the photodetector included in a fiber ring laser system was divided into two lines for measuring strain and AE individually. An optical filter demodulation technique was applied to measure the strain in the system.[6]

There are the following technical limitations in the system development.

1. It is difficult to emit a multi-wavelength laser stably using a fiber ring laser including a single optical amplifier.
2. A wavelength band more than 12 nm must be allocated to the respective FBG sensors to avoid signal interference in strain measurements because the reflective spectrum shifts by 12 nm when an FBG is subjected to a strain of 1 %.

A WDM component is available economically because a WDM technique in which a number of optical carrier signals are multiplexed onto a single optical fiber by using different wavelengths of laser light is widely used in the optical communication field. An optical filter for a coarse wavelength-division multiplex (CWDM) in which optical signals are separated by 20 nm in wavelength was used in the system to divide optical signals of four FBG sensors. The block diagram of the system is shown in Fig. 10.

The working mechanism of this system is the same as that of the system incorporating a single optical amplifier, as shown in Fig. 6. The lights reflected from four FBGs whose Bragg wavelengths are separated by 20 nm are divided into four lines according to the wavelength at the CWDM filter in the looped fiber. These divided lights at respective Bragg wavelengths are intensified by an individual optical amplifier and then are combined into a single optical fiber via an optical coupler. The lights are repeatedly amplified by being circulated through the looped fiber and eventually emit laser light at the respective Bragg wavelengths. Part of multi-wavelength laser light generated by the fiber ring laser is sent to another CWDM filter through the optical coupler in the looped optical fiber and is divided into four optical fibers with respect to the wavelength. Each laser at the Bragg wavelength of the respective FBG sensors is separated into two lines for measuring strain and AE through an optical coupler. The strain measurement line is connected to an

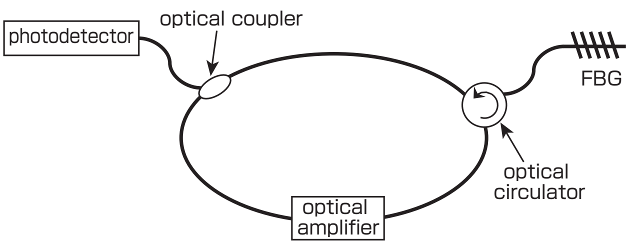

Fig. 6 A setup of a fiber ring laser system

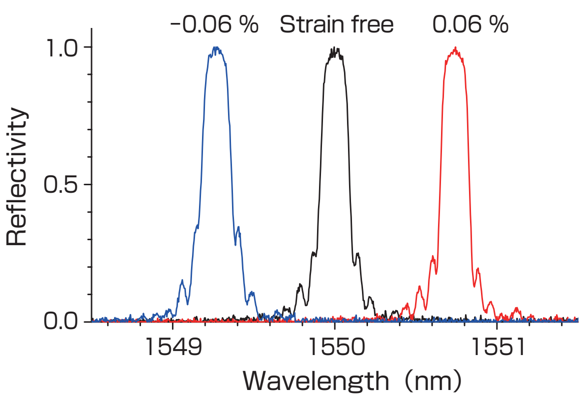

Fig. 7 FBG reflection spectrum shift when an FBG is strained by ±0.06 %

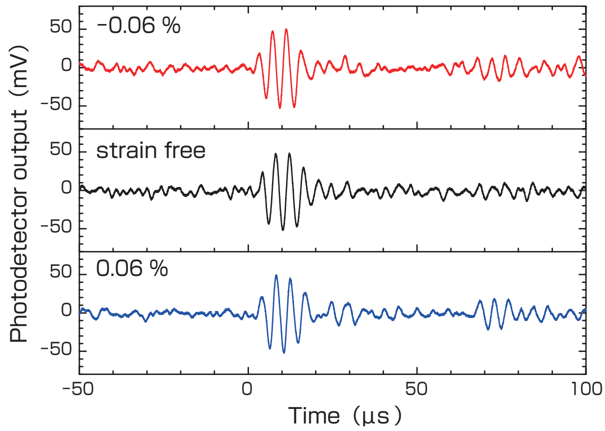

Fig. 8 An example of ultrasound detection using a fiber ring laser system in which the FBG is subjected to different strain levels

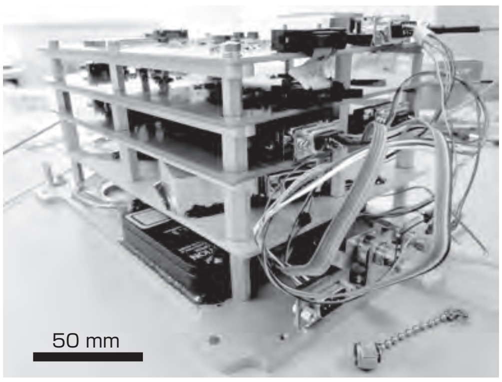

Fig. 9 A fiber-ring laser-based AE measurement system capable of installation on a rocket structure

optical filter for evaluating the strain. The strain applied to the FBG can be estimated from both the intensities of lights reflected from and transmitted through the optical filter. The AE measurement line is directly connected to a photodetector. A signal exceeding a threshold level that is predetermined to eliminate background noise is recorded as an AE signal. In Fig. 10, the two lines for measuring strain and AE are depicted only for an FBG with a Bragg wavelength of λ_1 for simplicity. In the actual system, the other three outputs have two lines for measuring strain and AE.[15]

Both strain and AE measurements of a solid rocket motor case and a vibration measurement of a liquid rocket engine in a liquid hydrogen atmosphere were performed using the 4-ch FBG sensor system. The vibration of the structure in a liquid hydrogen atmosphere was remotely measured via a waveguide rod with a piezoelectric sensor because piezoelectric sensors could not be installed in such an extremely low temperature atmosphere. An FBG could be installed onto a structure in a liquid hydrogen atmosphere, and the system could detect weak vibration components that conventional piezoelectric sensors had never detected. Furthermore, this system demonstrated that the simultaneous measurement of both strain and AE from four FBG sensors is possible.

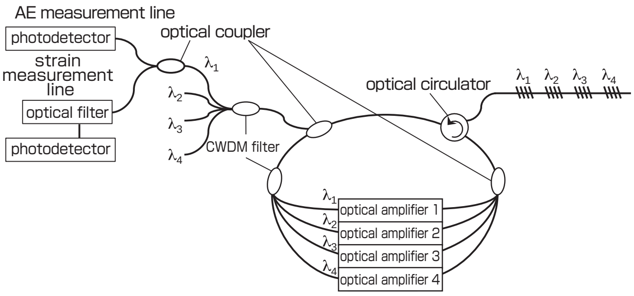

Fig. 10 A block diagram of a simultaneous multi-point system for measuring strain and AE

The lines for measuring strain and AE are depicted only for the output of the FBG whose Bragg wavelength is λ_1 for simplicity. In the actual system, each output of the respective FBG sensors has two lines for measuring strain and AE.

6 Conclusions

This research aimed to develop a multiplexed FBG sensor system featuring the simultaneous multi-point measurement of both strain and AE. The system development process is shown in Fig. 11. When the research project began, the technology of AE measurement with an FBG sensor was undeveloped, and AE detection using an FBG sensor had never been demonstrated. In the beginning of the project, we attempted to evaluate the AE detectability of an FBG sensor and to detect AE using an optical filter demodulation system that met the specification for installation on a rocket. Although an FBG itself possessed an excellent AE detectability, an FBG incorporated in an optical filter demodulation system lacked AE sensitivity. An operational

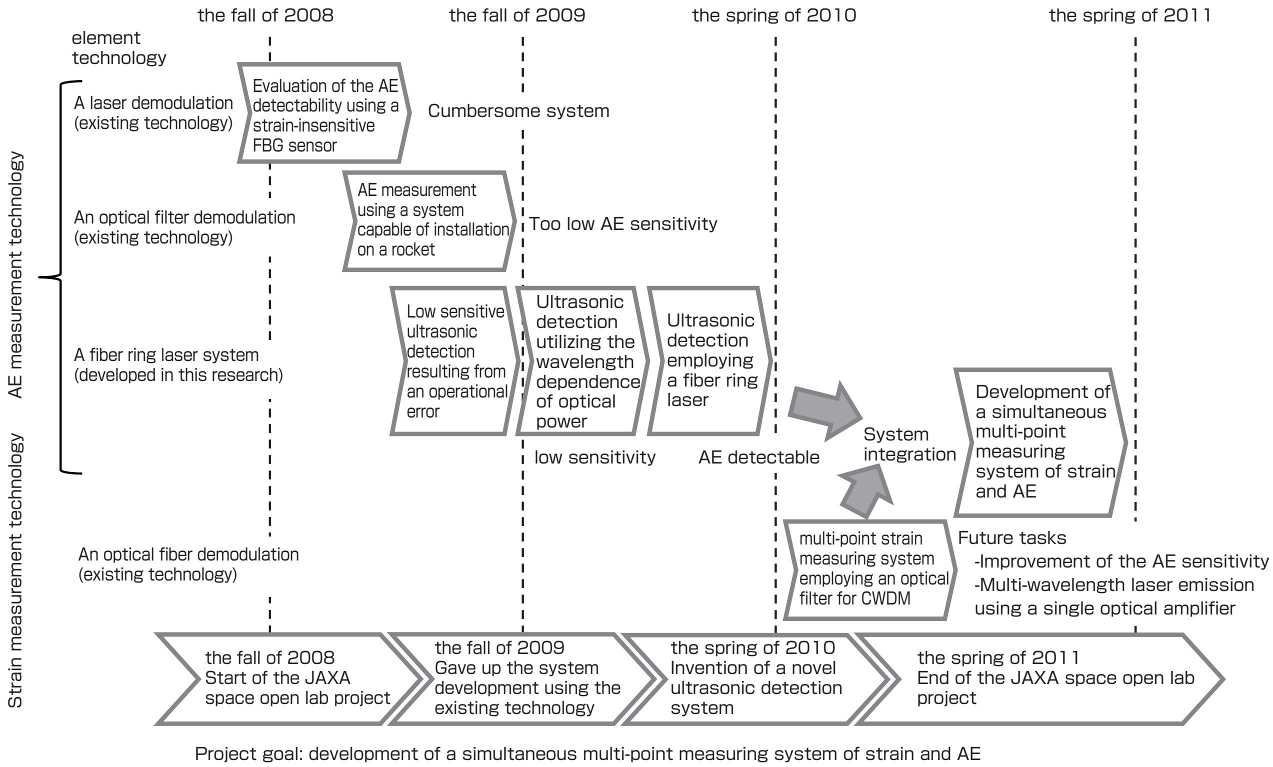

Fig. 11 The system development process

Table 2. Features of the AE measurement technology adopted in the present research

	Laser demodulation (existing technology)	Optical filter demodulation (existing technology)	Fiber ring laser system (developed in this study)
AE detectability	○(see Fig. 3)	×(cannot distinguish between AE and background noise)	○(see Fig. 8)
Installation to a space structure	×	○	○
Simultaneous measurement of strain and AE	×(*1)	○(*2)	○(*2)
System price (JPY) (*3)	6,000,000	1,000,000	500,000

(*1) It is necessary to add a broadband light source to measure strain.
(*2) Both strain and AE can be measured using a system including a single light source.
(*3) The price is for a 1-ch AE measurement system, excluding a function for evaluating strain.

error in an ultrasonic detection test brought a chance to conceive of a new AE measurement system using a fiber ring laser. A fiber ring laser system can detect vibration in a broadband range from mechanical vibration to ultrasound. The intensity of laser generated from a fiber ring laser is modulated by vibration impinging on an FBG sensor by utilizing the wavelength dependence of gain of the optical amplifier incorporated in the fiber ring laser. A simultaneous multi-point measuring system of both strain and AE was constructed by integrating a strain measurement system based on an optical filter demodulation technique into a fiber ring laser system. The features of the element technologies adopted in the present study are listed in Table 2.

A fiber ring laser system developed in the project can detect ultrasound up to 2 MHz, compared to commercially available FBG sensor systems which cannot detect ultrasound because the sampling rate is 1 kHz at most. In addition, a fiber ring laser system featuring a simple configuration, is small in size and lightweight and can be constructed inexpensively compared to conventional FBG sensor systems. However, the following technical tasks remain unsolved. A stable multi-wavelength laser oscillation cannot be realized by a fiber ring laser system including a single optical amplifier. Optical amplifiers are required for each FBG sensor for emitting multi-wavelength lasers at present. AE sensitivity of an FBG sensor incorporated in a fiber ring laser system is lower than that of piezoelectric sensors. We would like to solve these problems and expand the application of the fiber ring laser system not only to space structures but also to industrial machinery in the future.

References

[1] H. Jinyama: *Kaiten kikai no shindo shindan no saishin gijutsu to doko* (The latest technology and trends for vibrational diagnostics of rotary machinery), *Kensa gijutsu (Inspection Engineering)*, 17, No. 3, 29-35 (2012) (in Japanese).

[2] G. Wild and S. Hinckley: Acousto-ultrasonic optical fiber sensors: Overview and state-of-the-art, *IEEE Sensors Journal*, 8, 1184-1193 (2008).

[3] W.J. Staszewski, C. Boller and G.R. Tomlinson: *Health Monitoring of Aerospace Structures :Smart Sensor Technologies and Signal Processing*, 29-73, Wiley, West Sussex (2004).

[4] M. Majumder, T.K. Gangopadhyay, A.K. Chakraborty, K. Dasgupta and D.K. Bhattacharya: Fibre Bragg gratings in structural health monitoring - Present status and applications, *Sensors and Actuators A-Physical*, 147, 150-164 (2008).

[5] A. Othonos: Fiber Bragg gratings, *Review of Scientific Instruments*, 68, 4309-4341 (1997).

[6] M.A. Davis and A.D. Kersey: All-fiber Bragg grating strain-sensor demodulation technique using a wavelength-division coupler, *Electronics Letters*, 30, 75-77 (1994).

[7] N. Takahashi, K. Yoshimura, S. Takahashi and K. Imamura: Development of an optical fiber hydrophone with fiber Bragg grating, *Ultrasonics*, 38, 581-585 (2000).

[8] H. Tsuda, K. Kumakura and S. Ogihara: Ultrasonic sensitivity of strain-insensitive fiber Bragg grating sensors and evaluation of ultrasound-induced strain, *Sensors*, 10, 11248-11258 (2010).

[9] S. Kojima, A. Hongo, S. Komatsuzaki and N. Takeda: High-speed optical wavelength interrogator using a PLC-type optical filter for fiber Bragg grating sensors, *Smart Structures and Materials 2004: Smart Sensor Technology and Measurement Systems*, 5384, 241-249 (2004).

[10] J.R. Lee, H. Tsuda and Y. Akimune: Apodized fibre Bragg grating acousto-ultrasonic sensor under arbitrary strain using dual Fabry-Perot filters, *Journal of Optics A-Pure and Applied Optics*, 9, 95-100 (2007).

[11] H. Tsuda, E. Sato, T. Nakajima, H. Nakamura, T. Arakawa, H. Shiono, M. Minato, H. Kurabayashi and A. Sato: Acoustic emission measurement using a strain-insensitive fiber Bragg grating sensor under varying load conditions, *Optics Letters*, 34, 2942-2944 (2009).

[12] H. Tsuda: A Bragg wavelength-insensitive fiber Bragg grating ultrasound sensing system that uses a broadband light and no optical filter, *Sensors*, 11, 6954-6966 (2011).

[13] FBG Vibration Detection System, Apparatus and Vibration Detection Method Using the System (FBG shindo kenshutsu shisutemu, gai shisutemu o mochiita sochi oyobi shindo kenshutsu hoho), JPO Patent Publication 2011-196744 (in Japanese).

[14] H. Tsuda: Fiber Bragg grating vibration-sensing system, insensitive to Bragg wavelength and employing fiber ring laser, *Optics Letters*, 35, 2349-2351 (2010).

[15] [15] T. Nakajima, E. Sato, H. Tsuda, A. Sato and N. Kawai: Development of simultaneous measurement system for strain and AE using FBG sensors (for structural health monitoring of solid rocket motor composite chambers), *Transactions of the Japan Society of Mechanical Engineers - Part A*, 78, 728-741 (2012) (in Japanese).

Authors

Hiroshi TSUDA

Completed the doctorate course at the University of Tokyo in 1994. Doctor (Engineering). Has worked for the National Institute of Advanced Industrial Science and Technology since 1995 and has been a leader of the structural health monitoring research group since 2010. He was in charge of developing the optical measurement system.

Eiichi SATO

Completed the doctorate course at the University of Tokyo. Doctor (Engineering). Has worked for the Institute of Space and Astronautical Science since 1985 and is now serving as professor. He was in charge of providing experiments and administrating the research project.

Tomio NAKAJIMA

Received the master's degree in engineering from Tsukuba University in 1987. Worked for Nissan motors and IHI aerospace. Has worked for IHI Inspection & Instrumentation since 2005 and is now serving as manager. He was in charge of both designing and manufacturing the optical components incorporated in the measurement system and conducting experiments.

Akiyoshi SATO

Graduated from Aoyama Gakuin University in 1977. BS degree. Worked for Nissan motors. Now, works for IHI Aerospace and has been chief engineer since 2009. He was in charge of both designing and manufacturing the electrical components incorporated in the measurement system and conducting experiments.

Discussions with Reviewers

1 Overall evaluation

Comment 1 (Shingo Ichimura, AIST)

The paper describes the development of an FBG sensor system and its application to monitoring the health of a space structure. The major accomplishment of this study is to establish the technology for measuring strain and AE simultaneously using an FBG sensor. I think the development of a novel technology to detect AE using an FBG sensor in particular is especially worthy. However, the authors should write more clearly about the synthesiological approach that is the focus of the journal *Synthesiology*.

Comment 2 (Mitsuru Tanaka, AIST)

This paper is well worth reading because there are twists and turns in the story of the system development. I advise the authors to add a diagram sketching the twists and turns during the system development. I made several comments for better understanding of this paper.

2 Objectives and chapter titles

Comment 1 (Mitsuru Tanaka)

I think that the main point of the system development is not to improve high sensitivity, but is multifunctionality in the frequency domain. If it is so, readers are likely to misunderstand the authors' achievement because the terms relating to high sensitivity are often used in the manuscript. The manuscript in the chapter "Introduction" should be revised in accordance with this comment.

Answer 1 (Hiroshi Tsuda, AIST)

The major achievement of this study is indeed the development of an AE measurement system that has high sensitivity and is also compact. The multifunctionality in the frequency domain that allows the simultaneous measurement of both strain and AE can be achieved by combining the newly developed AE measurement system with a conventional strain measurement system.

Comment 2 (Shingo Ichimura)

It is better to change the chapter titles as follows: "4. Development of an AE measurement system employing an FBG" and "4.1 AE measurement by a laser demodulation technique."

Answer 2 (Hiroshi Tsuda)

The titles of chapter 4 and subchapter 4.1 were changed as suggested. In accordance with the change, the title of subchapter 4.2, "The attempt of AE measurement by an optical filter demodulation technique" was changed to "AE measurement by an optical filter demodulation technique."

3 Technical terms

Comment 1 (Shingo Ichimura)

The terms of "damage tolerance design" and "smart structures" are used in chapter 2. However, the concept of damage tolerance design, and the relation between damage tolerance design and smart structures are not well explained. The authors should add a supplemental explanation.

Answer 1 (Hiroshi Tsuda)

The supplemental explanation was added in the first paragraph of chapter 2.

4 Description of element technology

Comment 1 (Shingo Ichimura)

This paper shows measurement ranges and describes shortcomings of conventional vibration sensors, such as strain gauges and piezoelectric sensors. A table that compares the features and the measurement range of both an FBG sensor and conventional sensors would help the readers to better understand the topic.

Answer 1 (Hiroshi Tsuda)

As suggested, Table 1 showing the features of respective sensors, was added in the 4th paragraph of chapter 1.

Comment 2 (Shingo Ichimura)

The title of subchapter 3.1 is "The working principle and sensor function of an FBG." However, there is no explanation about the working principle in the subchapter. Moreover, there is a statement that says, "In such harsh environments, there is a time limitation of the application of FBG sensor…" This statement gives a contradictory impression to readers because there is a statement that says, "A fiber optic sensor can solve problems faced by electric sensors" in chapter 1. The authors should provide a consistent description.

Answer 2 (Hiroshi Tsuda)

As suggested, the title of subchapter 3.1 was changed, and a supplementary explanation was added to the end of the first paragraph of subchapter 3.1.

Comment 3 (Mitsuru Tanaka)

I cannot understand the necessity of the comparison between a laser demodulation technique and an optical filter demodulation technique. The authors should write more concisely or delete this comparison if the comparison is not essential to this paper.

Answer 3 (Hiroshi Tsuda)

The description in the second paragraph in subchapter 3.1 might cause misunderstanding. The description explaining that a dynamic change in the Bragg wavelength could be detected using both demodulation techniques was added there.

5 From the viewpoint of “synthesiology”

Comment 1 (Shingo Ichimura)

The authors mention that a novel vibration measurement principle utilizing the wavelength dependence of the light output of the light source was found by chance. The author should describe in detail the research process and approach that led to the finding of the new technology in subchapter 4.3. The research approach seems to be valuable and universal even for researchers in other fields.

Answer 1 (Hiroshi Tsuda)

The 3rd paragraph in subchapter 4.3 was revised and Figs. 5 (a) and (b) were added there. Moreover, Fig. 11 was added in chapter 6 to illustrate the system development process.

Comment 2 (Mitsuru Tanaka)

1. Describe in detail the research process that led to the use of a fiber ring laser.
2. A tunable laser was used as a light source in the system shown in Fig. 4. I would like to confirm whether a fiber ring laser consisting of four optical amplifiers is used as a light source in the system shown in Fig. 10.
3. I would like to confirm whether the allocation of frequency band is a problem to be solved in the future. If it is so, redraw Figs. 4 and 10 so that the present technology can be distinguished from the future tasks.

Answer 2 (Hiroshi Tsuda)

1. The research process that led to the usage of a fiber ring laser had been described in the 3rd paragraph in subchapter 4.3, and Figs. 5 (a) and (b) were added for better understanding. The system development process was schematically shown in Fig. 11 in chapter 6.
2. The fiber ring laser works as the light source in the system shown in Fig. 10. The system emits a laser by repeating optical amplification of a narrowband light at the Bragg wavelength of the FBG sensor.
3. In the present technology, optical amplifiers are required for the respective FBG sensors. The authors would like to develop a sensing system consisting of a single optical amplifier. Both the present technology and the future tasks are schematically shown in Fig. 11.

Comment 3 (Shingo Ichimura)

This paper deals with the R&D of an FBG sensor system for monitoring the health of an aerospace structure. The focus of the present paper is on the development of technology to overcome the technical barrier written in Note 2 of Table 1. The technical tasks confronting the AE measurement with an FBG sensor and the developed system are described in subchapter 3.2 and chapter 4, respectively. The research process is schematically shown in Fig. 11. However, the relation between the technical tasks and the solutions remains still vague. It is better to add a new table showing the features of AE measurement technology adopted in the present study.

Answer 3 (Hiroshi Tsuda)

Table 2 was added to chapter 6.

Comment 4 (Shingo Ichimura)

As listed in Table 1, there seems no technical task in strain measurement using an FBG sensor. However, strain measurement technology is listed in Fig. 11 that illustrates the system development process. I do not know what kind of technical tasks have been solved using an optical filter for CWDM. The authors should revise the manuscript, Fig. 11 and Table 1 for better understanding.

Answer 4 (Hiroshi Tsuda)

The aim of our JAXA Space Open Lab project is to develop a multi-channel FBG sensor system that measures both AE and strain simultaneously. The developed system was built by integrating a novel AE measurement system into a conventional strain measurement system. For better understanding of the developed system configuration, a column indicating that an FBG can measure both AE and strain simultaneously was added to Table 1. Moreover, Fig. 11 was revised to show which element technology was used to measure AE and strain. The developed system integrating an AE system into a strain measurement system is compact because the system shares the same light source. The feature of compactness is listed in Table 2. The manuscript was modified to clarify that the developed system is capable of measuring both AE and strain simultaneously.