Development of multi-point fiber Bragg grating sensors combined with incoherent FMCW optical ranging system

Dissertation Abstract

DEVELOPMENT OF MULTI-POINT FIBER BRAGG GRATING SENSORS COMBINED WITH INCOHERENT FMCW OPTICAL RANGING SYSTEM

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Abstract

My dissertation presents and discusses a method to develop an FBG interrogator for long-range structural health monitoring systems (SHMS) applications. A three-points FBG sensor was successfully analyzed by a combination of incoherent frequency modulated continuous wave (I-FMCW) and a vertical-cavity surface-emitting laser (VCSEL). Our system can provide not only reading out the temperature and strain by using FBG sensors, but also identifying the location of the installed FBGs. We demonstrate our proposed system to measure long-range, temperature, and strain measurements. The measurement result shows that our system can clearly distinguish all FBGs installed in a totally 6.6 km-long optical fiber with 1.5 m spatial resolution. The Bragg wavelength shifts of the FBGs according to temperature changes were successfully measured. As well as measuring temperature, we also conducted strain measuring. Our system only experimentally tested in the temperature range 25^{o}C ~ 45^{o}C and in the strain range of 369 με ~ 2137 με. Nevertheless, there will be opportunities to span more large temperature and strain range by increasing injection current to sweep more wavelength change. Even though our system tested only three FBGs in the experiment, the system can be scaled up to more FBGs and extended scale areas. Because we employed a low-cost available VCSEL, our proposed system offers a low-cost and straight forward FBG interrogator for a long-range SHMS.

Keywords: VCSEL, FMCW, FBG, SHMS.

I. Introduction

In recent years, technology is rapidly growing up in the world. Now, many countries have a lot of huge of civil infrastructures like skyscrapers, water DAMs, tunnels, long bridges, and highways represent an enormous financial investment. These buildings can be seen not only in developed countries but also in developing countries. Unfortunately, several accidents caused structures collapses that have been killed many people [1]. Therefore, engineers, researchers, and also stakeholders have been struggling to overcome this problem.

On the other hand, many advances in sensing, computing, and communications create a new technology to solve the health of structures detection, which is a structural health monitoring system (SHMS) [2]. SHMS is defined as a process of detecting structural conditions due to damage or deterioration by comparing structural responses obtained by various physical parameters using many kinds of sensors, both temporally and spatially. The process in SHMS covers sensors installation, comparative feature extraction, normalization, and estimation for diagnosis of structural health conditions [3]. By using this system, structures continuously and automatically detect the damage, characterize it (recognize, localize, quantify, or rate) and report it [4].

To detect some physical parameters in structures, SHMS usually employs many kinds of sensors such as a piezoelectric sensor, strain gauge, electrical time-domain reflectometers (ETDR), a microelectromechanical sensor (MEMS), an eddy current sensor, and fiber optic sensor. The sensor mentioned at last, fiber optic sensor, has more advantages than other sensors such as it is very compact and easily embedded into structures. In addition, fiber optic sensors also offer the capability to perform integrated, distributed measurements, and immune to electromagnetic interference; therefore, it suitable for SHMS [4][5].

A fiber optic sensor widely used in SHMS is fiber Bragg grating (FBG). Due to FBG is leading on application-wide multiplexing of measurement points, FBG is called the king of the quasi-distributed sensors [2]. Several FBGs can be clearly resolved by using the same fiber line by multiplexing many FBGs in the wavelength domain [4]. Since FBG has a unique core whose periodic refractive index variation, a light whose wavelength satisfied the Bragg condition can measure strain and temperature [6]–[8]; those are critical parameters in SHMS.

The main issue FBG interrogator for SHMS applications are long-range remote sensing and spatial resolution capability. Besides that, over the past decade at industrial sectors have been paid in attention to reduce cost and made more competitive[1]; consequently, there is challenging in low-cost systems for FBG interrogator. Therefore, our dissertation proposes an FBG interrogator not only for long-range remote multi-point sensing but also offers low-cost systems.

Generally, the simplest way to interrogate FBG is usually by using an optical spectrum analyzer(OSA). Due to OSA has limited scanning and high-cost in the operational system, a charge-coupled device (CCD) spectrometer and using tunable Fabry-Perot filters succeed in replacing an OSA to realize wavelength speed scanning up to 20 kHz [9][10]. However, it may be rather difficult to be applied in long-range measurement because this system needs high power for the broad-spectrum light source, which is launched into FBG. For this reason, not only from the university and research center but also from the industry have proposed other methods to interrogate FBG, which are compact, low-cost, and effective in real time.

Among the FBG interrogate methods, the wavelength-swept laser is now widely used due to high intensity, narrow lasing, and wide wavelength tuning range [11]. Many kinds of wavelength-swept lasers, either laser diode (LD)-based or fiber laser-based, have been developed by using external cavity tunable LD, piezo transducer-based tunable Fabry-Perot filter, polygonal mirror scanner, and Fourier-domain mode-locking (FDML). Sweep rate can be achieved fast and widely [12], [13], but those techniques require a high cost for providing some optical or mechanical components. On the other hand, a vertical-cavity surface-emitting laser (VCSEL) has been demonstrated as a low-cost wavelength-swept by simply changing the injection current or temperature [14]–[17]. VCSEL has demonstrated remarkably good stability and reproducibility of the output frequency [18], [19] and make it promising for low-cost application involving wavelength-swept lasers such as tomography [20], object profiling [14], [21], and high-speed communication [22].

The large multiplexing and lower crosstalk of the FBGs sensors through both simulation and experiment could be carried out by optical reflectometry based measurement either time domain or frequency domain [23]. Time-domain reflectometry uses optical pulses launched into an optical fiber and processes backscattered signals. In order to increase the spatial resolution, the pulse width has to be reduced. However, this method requires ultrafast light modulation and detection, which is very expensive. On the other hand, since frequency-domain reflectometry measures interference of Rayleigh signal from reference and reflected signal, the spatial resolution is governed by the frequency range [24]. Besides, frequency domain reflectometry also offers high signal and noise ratio (SNR) as well as better spatial resolution than time-domain reflectometry.

Frequency-domain reflectometry can be divided into two categories; a coherent optical frequency domain reflectometry (C-OFDR) and incoherent frequency-domain reflectometry (I-OFDR). For long-range measurement applications, I-OFDR has promisingly opportunity instead of C-OFDR because of I-OFDR is the non-interferometric, which no requires a narrow linewidth laser and ultra-linearly swept optical source [25], [26]. By using I-OFDR, Werzinger et al. reported that 20 FBGs could be successfully interrogated by vector network analyzer (VNA). The location of FBGs is calculated by the inverse Fourier transform of the frequency response. Hence VNA is quite costly, incoherent frequency modulated continuous wave (I-FMCW), a sub-group of the I-OFDR, offers much cheaper because of this system combine reference and reflected signal in the electrical domain by using electrical mixing component [27].

Long-range and low-cost FBG interrogator recently becomes an exciting research topic, especially in SHMS applications. In this research, we propose a combination of wavelength-swept by using VCSEL and I-FMCW optical ranging to develop a new system of FBG interrogator. A wavelength-swept tunable laser can be achieved by injection current on VCSEL in order to explore the spectrum of FBGs. Compare to the other technique, it needs only a low-cost component. Then, I-FMCW is also employed in our research for the purpose of multiplexing and localizing FBGs.

To realize this method, we set up a system consist of an I-FMCW ranging system and VCSEL as a light source. We make a program using National Instrument (NI) LabVIEW to control our system. In order to know the performance FBG Interrogator which is developed by using our method, we observe as follows: Long-range and spatial resolution capability, temperature measurement capability, strain measurement capability.

II Experiment

To realize FBG Interrogator for long-range SHMS, we combine VCSEL and I-FMCW. The setup of our system is illustrated in figure 1. A single-mode VCSEL emitting at 1560 nm is employed as a laser source. The temperature of the VCSEL is controlled to 20^{o}C trough Thermo Electro Controller (TEC). The VCSEL is sinusoidally intensity-modulated by the injection current modulation, and the modulation frequency is linearly swept in time from 10 MHz to 160 MHz with 50 Hz repetition frequency by the signal generator. The emitted light from the VCSEL is amplified up to 6 dBm by using the erbium-doped optical fiber amplifier and is then launched into single-mode fibers connecting with three FBGs (FBG1, FBG2, and FBG3) through the circulator. The specification of FBG1, FBG2, and FBG3 are shown in Table 1.

The reflected light from the FBGs is detected with the photodetector. The wavelength of the VCSEL is controlled by the injection current to measure the reflection spectrum of the FBGs through a laser driver. To confirm the possibility of remote sensing, we insert optical fibers, FO1, FO2, and FO3 between FBGs. The lengths of FO1 and FO2 are 1000 m and 5640 m, respectively, and the length of FO3 is selected from 40 m, 10 m, and 5 m. The ranging signal is generated by electrical mixing of the reflected signal and the reference signal by using the double-balanced mixer followed by the low pass filter (LPF), and then the ranging signal is sampled using the high-speed data acquisition (DAQ). The data acquisition board has two analog input channels with the sampling rate until 20 MS/s and a 12-bit resolution and synchronization channel. For measurement purposes, analog input 0 (AI.0) acquires ranging signal and analog input 1 (AI.1) acquires ILDsignal from laser driver. Due to the modulation frequency sweep is bidirectional with 10 ms of the frequency increasing section and 10 ms of the frequency decreasing section, we acquire a ranging signal only the frequency increasing section. To ensure starting data acquisition only from the beginning of the frequency section, a synchronization channel from the DAQ board is connected to the signal generator by using a transistor-transistor logic (TTL) signal, which is generated according to increasing and decreasing section. Then, In order to sweep the wavelength of the VCSEL, the injection current of the VCSEL is changed in stepwise [20] by using the programmable voltage source.

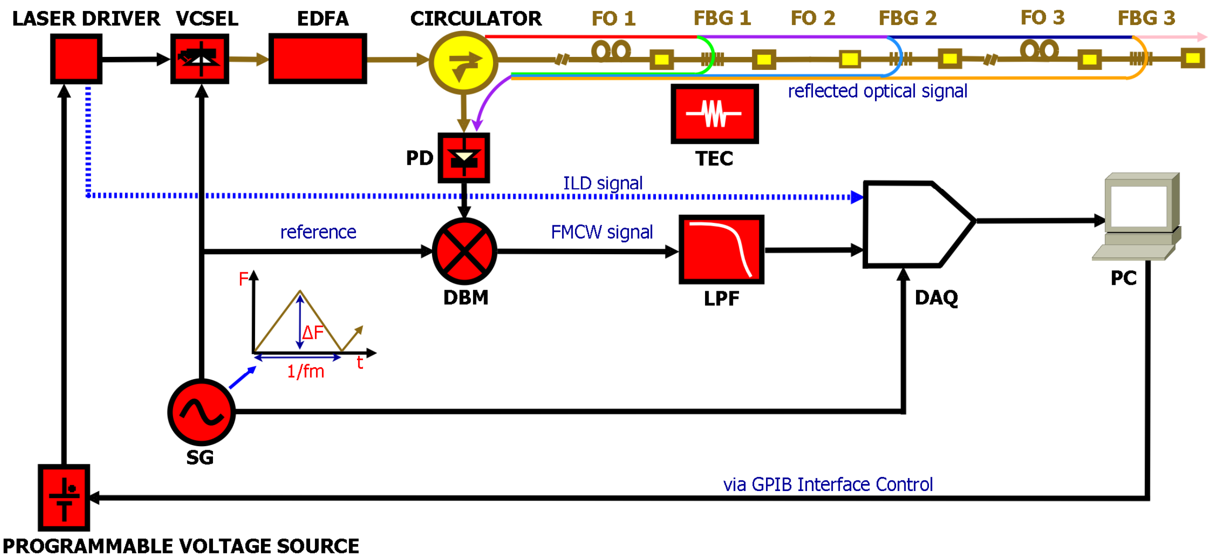

Figure1. Configuration of the proposed system for FBG interrogator.

Table 1. Specification of FBG1, FBG2, and FBG3.

	Bragg wavelength (nm)	Reflectivity (%)	Bandwidth (nm)
FBG1	1560.01	5.59	0.083
FBG2	1560.04	5.81	0.110
FBG3	1560.03	6.24	0.095

III Result and Discussion

Figure 2 shows the peak of Fresnel reflection of 1000 m-long optical fiber at 1.041 km with a signal to noise ratio (SNR) of 45 dB and the peak of Fresnel reflection of 6640 m-long optical fiber at 6.68 km with an SNR of 27 dB. The SNR of the 6640 m-long optical fiber is weaker than the Fresnel reflection peak for the1000 m-long optical fiber due to the attenuation of the optical fiber. Nevertheless, our system might be a possibility for long-range and large SHMS.

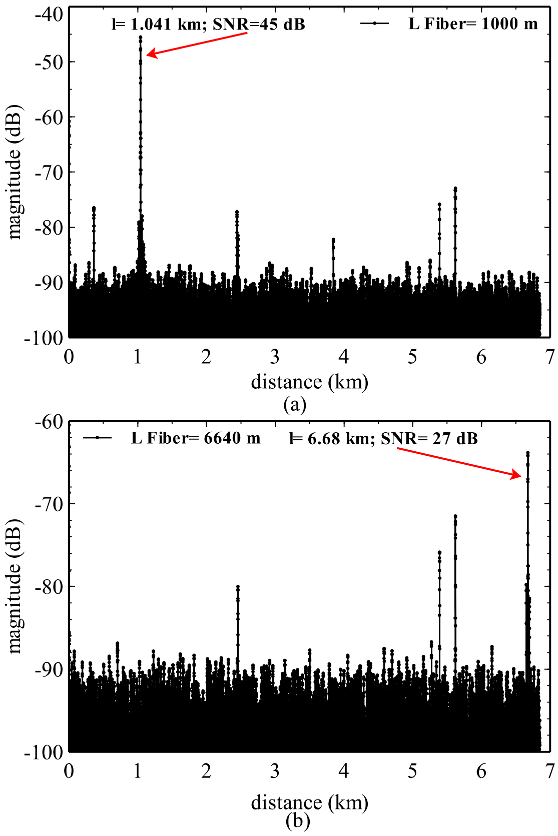

Figure 2. Measured beat spectrum of Fresnel reflection of an optical fiber with length of (a) 1000 m and (b) 6640 m.

After successfully tested our system to measure long-range optical fiber, we then install three FBGs into our system over 6.6 km in length. The lengths of FO1 and FO2 are 1000 m and 5640 m, respectively, in order to validate the capability of long-range FBG sensing, and the length of FO3 is short optical fibers between three optional lengths (40 m, 5 m, or 3 m) to confirm the spatial resolution and also identify the exact location of FBG installed. In this measurement, all of FBGs are kept in room temperature (23^{o}C) and unstrained condition.

We then measure the Bragg wavelength shift of the FBGs against the temperature change to evaluate the temperature sensitivity. In this experiment, the ambient temperature of FBG1 was increased from 25^{o}C to 45^{o}C in 5^{o}C step, and contrary the temperature of FBG2 and FGB3 are kept at room temperature. The reflection spectra of all FBGs are shown in figure 4. We find the reflection spectrum of FBG1 in figure 4(a) is shifted to longer wavelength according to the temperature increase, while the reflection spectra of FBG2 and FBG3 in figure 4(b) and (c), respectively, are unchanged. During the experiment, the room temperature is almost constant. Therefore the temperature of FBG2 and FBG3 are also unchanged.

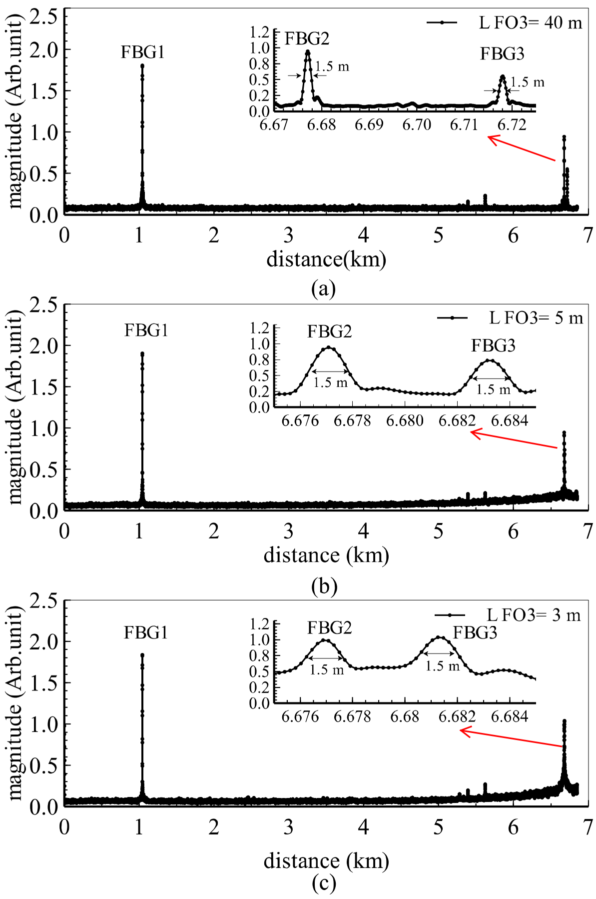

Figure 3 Measured beat spectrum for different FO3 length, (a) 40 m, (b) 5 m, (c) 3 m at the same temperature, and unstrained.

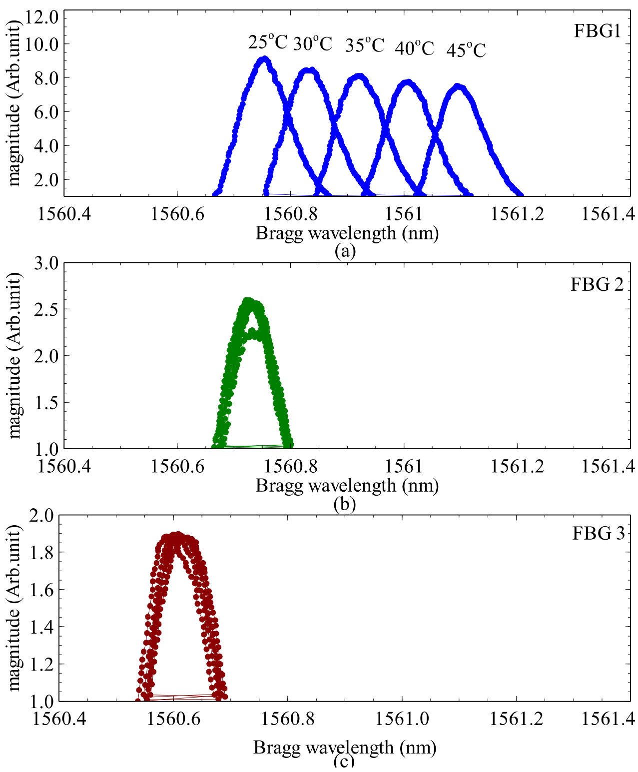

Figure 4. Spectrum of (a) FBG1, (b) FBG2, and (c) FBG3 when the temperature of FBG1 is changed.

Next, we examine only the response of FBG1 when the ambient temperature increase from 25ºC to 45ºC in 2.5 steps. Figure 5 shows the correlation between the temperature of FBG and the Bragg wavelength of FBG1. The Bragg wavelength of FBG1 is linearly increased with the temperature match with the reported article by Song et al. [28]. The expression shown in figure 5 also gives the temperature sensitivity of FBG1 is 17.3 pm/ºC and is almost the same as a typical FBG, which is reported by other researchers, which is between 11 pm/ºC ~ 14 pm/ºC [29]–[31].

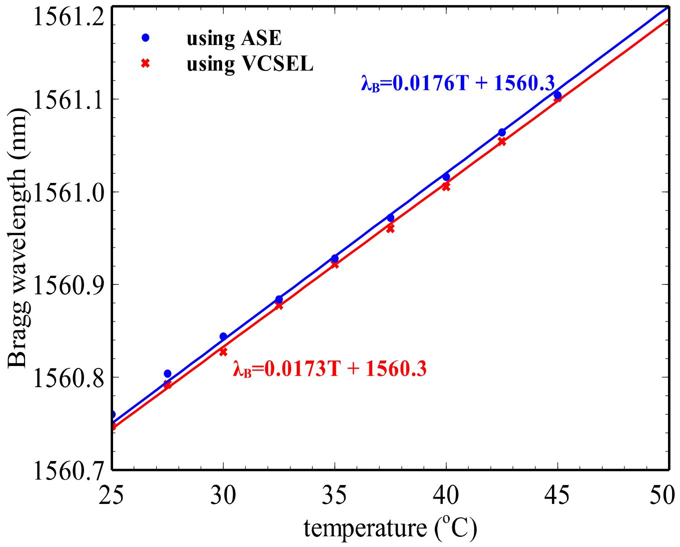

Figure 5. Transfer function of temperature FBG sensor.

We also measured the Bragg wavelength shift against the temperature change by using an OSA and an amplified spontaneous emission (ASE) as a broadband light source. The result is now also shown in same figure 5. The blue line expresses the result of temperature FBG measurement by using ASE and OSA, and the red line shows result measurement by using our system. Both results show almost the same trends and correlations.

Like temperature measurement, we also demonstrate the spectrum profile of FBGs as a function of the strain change. FBG1 and FBG2 are still in unstrained condition, and FBG3 is strained in the range of 369 με ~ 1076 με. The measured beat spectra are shown in figure 6(a), (b) and (c) for FBG1, FBG2, and FBG3, respectively. In figure 6(c), the Bragg wavelength of FBG3 is shifted to longer wavelengths with the strain. However, the Bragg wavelength of FBG1 and FBG2 are almost unchanged because FBG1 and FBG2 were unstrained as shown in figure 6(a) and (b).

Figure 7 shows the correlation between the strain and the Bragg wavelength of the FBG3. the Bragg wavelength is also linearly changed with the strain. From this figure, we also define the strain sensitivity is 0.29 pm/με, which is lower than a typical FBG strain sensitivity of 1.2 pm/με [29]–[32]. The relatively low sensitivity may be due to not optimized fixing of the FBG to the cantilever beam. We also compare to strain measurement results by OSA and ASE as a broadband light source. The result is also shown in figure 7. The blue line is a result measurement by using OSA and ASE, and the red line is a result measurement by using VCSELor FBG Interrogator which developed by the proposed method. Both results show almost the same trends and correlations.

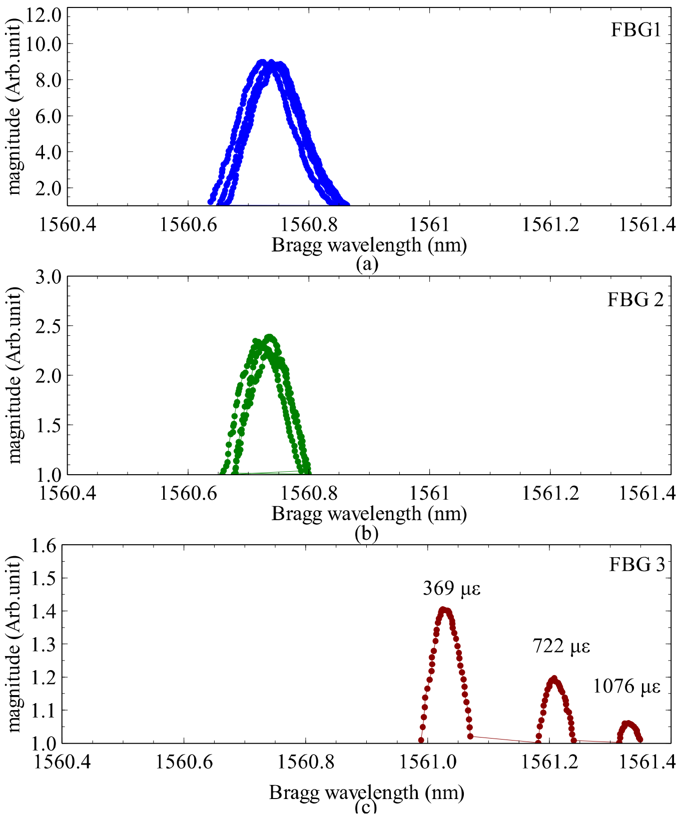

Figure 6. Spectrum of (a) FBG1, (b) FBG2, and (c) FBG3 when FBG3 is strained and FBG1 and FBG2 are unstrained.

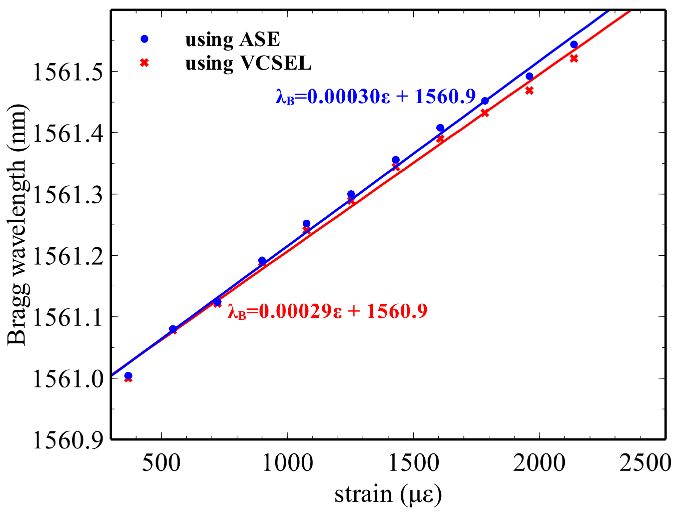

Figure 7. Transfer function of strain FBG sensor.

IV Conclusion

We have developed and tested a system to interrogate multipoint FBG sensors combined by the I-FMCW optical ranging system and a VCSEL. Our proposed system has been successfully to measure long-range distance, temperature sensing, and strain sensing. Our system has tested to measure temperature from 25°C to 45°C and strain from369μm to 2137μm. We offer a low-cost for multiplexing FBGs sensor interrogator as comparing with other techniques because our system uses commercially available VCSEL as a wavelength-tunable laser source. Our system also has great potential for remote SHMS because of the system capable of identifying the location of sensors from the beat frequency, and the physical parameters such as temperature and strain from the Bragg wavelength. Even though in our experiment, the system tested for monitoring temperature and strain, the developed system is able to be improved to measure various physical parameters such as stress, crack, and load in the monitored structure.

We also have presented the stability of our FBG interrogator for 23 hours as a temperature sensing measurement in our laboratory. Due to the FBG interrogator will be applied to monitor structures for a long time, it should be tested more a long time (for months and years). A field study of the proposed system is also needed to validate the effectiveness of detecting physical parameter change caused by damage of structures.

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令和 2 年 2 月 5 日

学位論文審査報告書（甲）

1．学位論文題目（外国語の場合は和訳を付けること。）

Development of multi-point fiber Bragg grating sensors combined with incoherent FMCW optical ranging system

(インコヒーレント FMCW 光距離センサを組み合わせた多点型光ファイバブラッググレーティングセンサの開発)

2．論文提出者　(1) 所　　属　電子情報科学　　専攻

(2) 氏　　名　DWI HANTO（ドゥイ ハント）

3．審査結果の要旨（600～650 字）

令和 2 年 2 月 5 日に第 1 回論文審査会を開催し、同日に口頭発表を実施し、その後に第 2 回審査委員会を開催した。慎重審議の結果、以下のとおり判定した。なお、口頭発表に対する質疑を最終試験に代えるものとした。

ビル、橋、ダムなどの大型構造物において、構造物内のひずみ分布や温度分布を測定して劣化を診断する Structural Health Monitoring System (SHMS) が重要になってきている。特定の波長の光のみを反射する光ファイバブラッググレーティング (FBG) は反射波長の変化からひずみや温度が計測可能な光素子であり、SHMS に有効であるが、SHMS として実用化するためには、FBG の多重化と信号分離を低コストで実現する必要がある。本研究では、同じ反射波長を持つ低反射率 FBG を使い、面発光レーザ (VCSEL) を光源に用いた光の干渉を利用しない FMCW 光距離センサを用いて、複数の FBG の位置と反射波長を同時に測定するシステムを開発した。VCSEL の注入電流変化により波長を変化させながら FMCW 光距離センサにより距離計測を行うことで、複数の FBG の反射波長の距離分布を測定する。開発したシステムにより、3 点の計測ではあるが、6.6 km に渡る温度変化やひずみ変化の分布計測を実現した。

以上の研究結果は、低コストな SHMS の新たな実現方法を提案したもので、大型構造物の健康診断に大きく貢献するものであり、博士（学術）に値すると判断した。

4．審査結果　(1) 判　　定（いずれかに○印）　(合　格)・　不合格

(2) 授与学位　博　士（　学術　）