Real-time measurement system for overlapping reflection signals of fiber Bragg gratings using high-speed wavelength-swept laser

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Abstract. We propose a real-time measurement system that prevents overlapping reflection signals in fiber Bragg gratings (FBGs). The system combines a wavelength-swept laser using Fourier domain mode-locking (FDML) and a buffer stage with three optical paths to obtain a high-speed measurement rate of 304.2 kHz. Systems using high-speed wavelength-swept lasers are affected by the propagation time (delay) of the optical fiber. The delay causes problems such as inaccurate measurements, difficulty in distinguishing FBG reflection signals, and overlapping FBG reflection signals. To prevent these problems, we introduce a method for pulse modulation of a wavelength-swept laser by a fiber switch. This method allows for correction of delays by extracting and identifying only the reflection signal of the FBG at a specific wavelength. By identifying the reflection signals of all FBGs, the overlapping signals can be determined. Accordingly, we devise a measurement method that uses a fiber switch to shade light in the wavelength region of one FBG with overlapping signals from the wavelength-swept light of the laser. This method suppresses overlapping and allows only the reflection signal of the other FBGs to be extracted and demodulated. The proposed system uses bidirectional forward and backward scans with the wavelength-swept laser, such that the shaded FBG signals can be demodulated with either scanning direction. We demonstrate that the system using a three-buffered FDML laser can simultaneously measure the strain or vibration of FBGs installed at arbitrary distances. © The Authors. Published by SPIE under a Creative Commons Attribution 4.0 International License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: 10.1117/1.OE.61.7.076114]

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1 Introduction

Optical fiber sensors have proven to be a powerful tool for measuring the state of materials and structures with high speed and sensitivity.1–5 The use of light scattering, interference, modulation, and multicore fibers can improve the performance of optical fiber sensors.6–14 The fiber Bragg grating (FBG) is a point-type strain and vibration optical sensor widely used in science and engineering because it is easier to manufacture and better adapts to various measurement conditions than other optical fiber sensors.1,5 Structural health monitoring for qualitative damage assessment through acoustic imaging and high-speed measurement of vibrations exceeding several tens of kilohertz has been reported.15–21

In addition, FBGs have drawn attention as ultrasonic receivers for their diverse applications, including underwater applications and structural defect detection.15–21 For FBGs to function as ultrasonic receivers, the development of a high-speed measurement system that interrogates multiple FBGs is necessary. For the purpose, a system with a simple combination of a wavelength-swept laser and an optical detector can be configured. This system can perform a high-speed measurement of multiple FBGs simultaneously.22–28 Further speeding up the wavelength-swept lasers leads

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to a measurement system for broadband ultrasonic receivers. The measurement rate is determined by the sweep rate of the laser. Recently, buffered Fourier domain mode-locked (FDML) lasers, which use an optical system called a buffer stage to sweep wavelengths multiple times, have been devised to further increase the sweep rate.\textsuperscript{29-31} This type of laser has been used as a light source in medicine to achieve the highest imaging speed in optical coherence tomography.\textsuperscript{32} To measure FBGs installed at a short distance, we have used a two-buffered FDML laser at a measurement rate of 202.8 kHz.\textsuperscript{33}

However, measurements using high-speed wavelength-swept lasers are affected by the propagation time (delay) of the optical fiber that relays the measurement system and FBG. In fact, the delay reduces the measurement accuracy of FBGs. Thus, delay compensation has been developed using optical frequency combs,\textsuperscript{34} fiber Fabry–Perot (FFP) etalons,\textsuperscript{35} and bidirectional laser scanning.\textsuperscript{33,36} On the other hand, for distant FBGs, their reflection signals are folded back within the laser sweep period, hindering their identification. Methods for modulation of the laser sweep frequency\textsuperscript{37} and pulse modulation of the laser swept light\textsuperscript{38} have been reported for identification. However, no study is available on identification methods for buffered FDML laser, and high-speed measurements have not been achieved using this laser. Furthermore, when FBGs are placed at arbitrary distances, their reflection signals are close together, causing overlapping. Overlapping FBG reflection signals are difficult to identify and demodulate. Very few methods are available to handle this problem in wavelength-swept lasers. Therefore, the wavelength and installation distance of FBGs can be properly selected to avoid overlapping, but this limits the measurement flexibility. Furthermore, as multiplexing of FBGs allows increasing the sensor density, solving overlapping becomes essential.

In recent years, advanced and innovative research on demodulation of overlapping signals has been conducted, resulting in methods using genetic algorithms, search trees, machine learning, deep learning, and other techniques.\textsuperscript{39-42} In addition, training data of ideal reflection signals of FBGs have been generated through simulations to validate the developed methods. Although many experimental verifications are expected in the future, fundamental calculations can take several milliseconds for computation, even for fast algorithms, possibly impeding real-time operation.

We propose a measurement system using a three-buffered FDML laser for high-speed real-time measurement of overlapping FBG reflection signals. The laser sweep rate is 304.2 kHz with a bandwidth of 28 nm. In addition, the system uses pulse modulation of swept laser light to identify the reflection signals of FBGs at arbitrary distances. The identification results of the FBG reflection signals are used to determine overlapping. If overlapping between two FBGs is identified, light in the wavelength region of one overlapping FBG is shaded by a fiber switch (FSW) from the wavelength-swept laser light. This optical manipulation allows only the reflection signal of the other FBG with overlapping signal to be detected and demodulated. As the shaded FBG is measured during the forward or backward laser scan, our approach can demodulate all FBGs while preventing complete signal loss. In addition, it is suitable for high-speed real-time measurements because overlapping can be solved by simply adjusting the FSW operation without complex signal processing.

Buffered FDML lasers with multiple wavelength sweeps can achieve a very high measurement rate. On the other hand, the number of detected reflection signals of FBGs can increase by several times compared with that of a typical laser, increasing the possibility of signal overlapping, especially in high-density FBG setups. Our measurement system suppresses signal overlapping in the buffered FDML laser to enable flexible high-speed FBG measurements. We demonstrate that the proposed measurement system with a three-buffered FDML laser allows the installation of FBGs at arbitrary distances and can measure strain and vibration with overlapping correction.

2 Experimental Setup

2.1 FBG Measurement System

Figure 1 shows the proposed measurement system using a three-buffered FDML laser. The three-buffered FDML laser consists of an FDML laser, an optical amplifier, an FSW, and a buffer stage...
with three optical paths. The FDML laser is a ring-cavity laser that uses a fiber Fabry–Perot tunable filter (FFP-TF, Micron Optics). The laser is controlled by a sweep signal \( V_S \) from the oscillator (33612A, Agilent) and operates at sweep rate \( f_m = 50.7 \) kHz and sweep bandwidth \( \Delta \lambda = 60 \) nm. The FDML laser sinusoidally sweeps the oscillation wavelength from short to long wavelengths (forward scan) and from long to short wavelengths (backward scan). The optical amplifier (SOA1013, Thorlabs) magnifies the light emitted by the FDML laser. The amplified light is injected into an FSW (NSSW, Agiltron) with a rise/fall time of 100 ns. The sweep control signal \( V_S \) and pulse control signal \( V_P \) for the FDML laser are controlled by the oscillator having two channels, and the two signals are output synchronously. The FFP-TF and most of the optical fibers that make up the FDML laser are set at a constant temperature of 25°C using a thermal chamber (SLC-25A, Mitsubishi Electric Engineering).

During measurement using the buffered FDML laser, the FSW is controlled by \( V_P \) with oscillator pulse width (PW) \( t_{PW} \approx 3 \) \( \mu s \) (\( \sim 1/6 f_m \)), as shown in Fig. 1, to extract light in the center wavelength region of the forward and backward scans. The extracted light enters the buffer stage that is branched into three optical paths. The buffer stage has delay fibers of 670 and 1340 m with delays of 3.3 (\( 1/6 f_m \)) and 6.6 \( \mu s \) (\( 2/6 f_m \)), respectively. Thus, when the light extracted by the FSW is injected into the buffer stage, triple-multiplexed light in the forward and backward scans is generated owing to the delays between the optical paths.

The measurement system uses bidirectional forward and backward scans of the FDML laser with sweep rate \( f_m = 50.7 \) kHz to obtain a measurement rate of 101.4 kHz (\( 2 f_m \)). The measurement system then performs a triple-multiplexed wavelength sweep using the triple-buffer stage to increase the measurement rate to 304.2 kHz (\( 6 f_m \)). For identification of overlapping FBG signals, the measurement system adjusts the FSW as detailed in Sec. 2.2.

The emitted light from the three-buffered FDML laser is split by a coupler and enters optical channel \( K (= 1, 2) \) connected to an FBG sensor. FBG\(_{KJ} \) (\( J = 1, 2, 3 \)) has Bragg wavelength \( \lambda_{KJ} \) of 1540, 1550, and 1560 nm, respectively, with reflectance of \( \sim 80\% \) and half-width of \( \sim 0.2 \) nm. FBG\(_{1J} \) in optical channel 1 is installed in a general wavelength order, while FBG\(_{2J} \) in optical channel 2 can be installed at an arbitrary position. This verifies that the proposed system can handle both general and arbitrary installations for measurement. Offset fibers with lengths \( L_{OF1} \) and \( L_{OF2} \) are inserted in front of FBG\(_{2J} \) and FBG\(_{3J} \), respectively, such that they can be placed at arbitrary installation distances. Reference position \( P_S \) is the distance corresponding to the fiber length at which the wavelength sweep characteristics of the laser are measured. Therefore, when the installation position of the FBG exceeds reference position \( P_S \), a delay occurs owing to the propagation time of the optical fiber. Installation distances \( L_{KJ} \) for each FBG\(_{KJ} \) are given in Table 1.
The reflected light of the FBGs from each optical channel is received by the corresponding detector ($D_K$), and the detector signals ($V_{DK}$) are input to an analog-to-digital converter (ADC). Detector $D_3$ receives the optical output of the buffered FDML laser, and detector signal $V_{D3}$ is input to the converter (5170R, NI), which has a field-programmable gate array (FPGA) with a sampling frequency of 250 MHz to calculate the peak times of the FBG reflection signals from $V_{D1}$ and $V_{D2}$ and transfer them to a computer.$^{36}$ The computer converts the peak time into a reflection wavelength based on the wavelength sweep characteristics of the laser. In experiments, pulse modulation of the FSW is used to identify the reflection signal of each FBG and handle the overlapping, and the reflection wavelength of each FBG is measured at a rate of 304.2 kHz.

The measurement system is implemented in the NI LabVIEW programming language. Figure 2 shows a screenshot of the measurement system interface. The system uses signal

![FBG interrogation System with Three-Buffered FDML Laser](image)

**Table 1** Installation distance of each FBG.

<table>
<thead>
<tr>
<th>Optical channel $K$</th>
<th>FBG$_{KJ}$</th>
<th>Bragg wavelength $\lambda_{KJ}$ (nm)</th>
<th>Installation distance $L_{KJ}$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FBG$_{11}$</td>
<td>1540</td>
<td>4.23</td>
</tr>
<tr>
<td></td>
<td>FBG$_{12}$</td>
<td>1550</td>
<td>7.54</td>
</tr>
<tr>
<td></td>
<td>FBG$_{13}$</td>
<td>1560</td>
<td>11.95</td>
</tr>
<tr>
<td>2</td>
<td>FBG$_{21}$</td>
<td>1540</td>
<td>$10.75 + L_{OF1}$</td>
</tr>
<tr>
<td></td>
<td>FBG$_{22}$</td>
<td>1550</td>
<td>$16.32 + L_{OF1} + L_{OF2}$</td>
</tr>
<tr>
<td></td>
<td>FBG$_{23}$</td>
<td>1560</td>
<td>$5.12 + L_{DF1}$</td>
</tr>
</tbody>
</table>

![Fig. 2 Screenshot of FBG measurement system interface.](image)
processing to identify and delay-correct the reflection signal of each FBG per optical channel. After detecting overlapping, real-time measurement begins. The data volume of the peak wavelengths of all the FBGs measured by the system is \(\sim 14.6 \text{ MB/s}\), which can be stored in a commercially available external hard disk drive. The proposed measurement system allows real-time observation and recording of wavelength changes caused by strain and vibration in each FBG per optical channel.

### 2.2 Signal Processing for Overlapping FBG Signals

Figure 3 shows the signal processing flow of the proposed measurement system. The system first uses pulse modulation of the laser to identify the reflection signal of each FBG.\(^{38}\) This process adjusts \(t_{PW}\) of the optical FSW to \(\sim 1 \mu s\) and extracts only light in the wavelength region of a specific FBG per forward and backward scan. Hence, only FBG reflection signals at specific wavelengths are extracted and identified per scan. As the buffered FDML laser has a triple-wavelength sweep, three reflection signals can be detected and identified simultaneously. This process is performed for every FBG, completing signal identification for all the FBGs [Fig. 3(a)].

To compensate for delays owing to the FBG position, we use bidirectional scan for the wavelength-swept laser. Light in the wavelength region of a specific FBG is simultaneously extracted by the FSW in both the forward and backward scans. This operation allows the delay to be corrected by obtaining time difference \(t_D\) between the reflection signals by the forward and backward scans [Fig. 3(b)].\(^{33,38}\)

The detection status of the reflection signal of each FBG per scan can then be checked. Hence, it is easy to determine close FBG reflection signals that cause overlapping depending on the FBG installation position and wavelength. We set the occupied wavelength band of each FBG to 3 nm. The decision process identifies overlapping when the reflection signals of the FBGs are closer than 3 nm. In our laser, a wavelength change of 3 nm corresponds to a time variation of \(\sim 0.3 \mu s\). Therefore, an overlap is determined when two reflection signals occur within \(\sim 0.3 \mu s\).

If overlapping is not detected, the laser light is emitted at \(t_{PW} \approx 3 \mu s\) and the reflection signals of the FBGs are detected [Fig. 3(c)]. On the other hand, if the signals overlap, the light in the wavelength region of one overlapping FBG is shaded from the wavelength-swept laser light with shading width \(t_{PL} \approx 1 \mu s\) [Fig. 3(d)]. As a result, the reflection signals of one overlapping FBG are suppressed, and those of the other overlapping FBG can be demodulated. The shaded FBG can be demodulated by either forward or backward scanning of the buffered FDML laser. This completes the signal processing shown in Fig. 3 of the measurement system, and real-time measurements can begin afterward.

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**Fig. 3** Signal processing flow for overlapping FBG reflection signals.
3 Experimental Results

3.1 Characteristics of Three-Buffered FDML Laser

Figures 4(a) and 4(b) show the output spectrum of the FDML and the three-buffered FDML lasers. The optical output was measured using an optical spectrum analyzer with a time average of 10. The FDML laser was driven at sweep rate $f_m = 50.7$ kHz with a center wavelength of 1550 nm and a sweep bandwidth of $\sim 60$ nm. The buffered FDML laser extracted light in the central wavelength region of the FDML laser using the FSW, as shown in Fig. 1. The extracted light was then injected into the buffer stage with three optical paths to attempt triple multiplexing of the wavelength sweep. Therefore, the buffered FDML laser had an optical output with a center wavelength of 1550 nm and a sweep bandwidth of $\sim 28$ nm.

Next, the wavelength sweep characteristics of the buffered FDML laser were evaluated by an optical system using a wavelength monitor. Figure 5 shows the results of the sweep characteristics of the buffered FDML laser for sweep period $T_m = 19.7$ $\mu$s ($1/f_m$). Six sweeps of triple forward scans ($F_1$, $F_2$, and $F_3$) and triple backward scans ($B_1$, $B_2$, and $B_3$) were obtained by the buffer stage with three optical paths. Therefore, a measurement rate of 304.2 kHz ($6f_m$) was achieved when measuring the reflection wavelength of the FBG. The measurement system performed signal processing as shown in Fig. 3 to determine overlapping. Then, using the sweep characteristics of the buffered FDML laser shown in Fig. 5, the reflection wavelength was converted from the time of the FBG reflection signal to the reflection wavelength, and real-time measurements were performed. The FDML laser sweeps the oscillation wavelength in a sinusoidal manner. This system measures the wavelength sweep characteristics in advance using a wavelength monitor and applies an eighth-order polynomial approximation to the sinusoidal waveform in each sweep scan. In the experiment, the obtained polynomial approximations are used to convert the FBG reflection signals from time to wavelength.

![Fig. 4 Output spectrum of (a) FDML laser and (b) three-buffered FDML laser.](https://www.spiedigitallibrary.org/journals/Optical-Engineering)

![Fig. 5 Sweep characteristics of three-buffered FDML laser.](https://www.spiedigitallibrary.org/journals/Optical-Engineering)
Identification and Correction of Overlapping FBG Signals

Figures 6(I) and 6(II) show the FBG reflection signals in optical channels 1 and 2, respectively. The offset fibers for optical channel 2 were set to $L_{OF1} = 1000$ m and $L_{OF2} = 1000$ m. Figures 6(I-a) and 6(II-a) show the results from the buffered FDML laser with $PW \approx 3 \mu s$. The buffered FDML laser provided six optical pulses in forward scans ($F_1$, $F_2$, and $F_3$) and backward scans ($B_1$, $B_2$, and $B_3$). The time interval of the pulses was $3.3 \mu s$ ($1/6 f_m$). Optical channel 1 corresponded to a general FBG installation, where each FBG was installed in order of wavelength and short distance, as given in Table 1. Therefore, the order of detection of the reflection signals of the FBGs was easily identified. Eighteen reflection signals were detected in three FBGs over six sweeps. On the other hand, as optical channel 2 was set in an arbitrary wavelength order and the installation distance was substantially different across FBGs, the detection order of the FBG reflection signals was difficult to determine.

Identification using pulse modulation was performed in the forward scan of the buffered FDML laser. The pulse width was adjusted to $t_{PW} \approx 1 \mu s$. Figures 6(I-b)–6(I-d) show the identification results for FBG11, FBG12, and FBG13, respectively, and optical channel 1. Figures 6(II-b)–6(II-d) show the identification results for FBG21, FBG22, and FBG23, respectively, and optical channel 2. By using pulse modulation, only the reflection signals of specific FBGs in forward scans ($F_1$, $F_2$, and $F_3$) were extracted. In optical channel 2, where the offset fibers were installed, the reflection signals had delays because of distant FBGs. The reflection signals of FBG12 in optical channel 1 were $t_{F_1}^{F_1} = 1.70 \mu s$, $t_{F_2}^{F_2} = 4.96 \mu s$, and $t_{F_3}^{F_3} = 8.24 \mu s$. The reflection signals of FBG22 in optical channel 2 were $t_{F_1}^{F_1} = 21.50 \mu s$, $t_{F_2}^{F_2} = 24.77 \mu s$, and $t_{F_3}^{F_3} = 28.05 \mu s$. Thus, FBG22 was delayed with respect to FBG12 by $\sim 19.8 \mu s$ owing to $L_{OF1} = 1000$ m and $L_{OF2} = 1000$ m. This delay was equal to one cycle of a sweep period ($T_m$). FBG21 and FBG23 were delayed with respect to FBG11 and FBG13 by $\sim 9.9 \mu s$, being half of a

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Identification by pulse modulation was also performed for the backward scan of the buffered FDML laser, confirming the identification of individual FBG reflection signals.

Next, to examine in detail the identification by using pulse modulation, length $L_{OF2}$ was changed and the FBG reflection signal in optical channel 2 was measured. Figure 7(a) shows the FBG reflection signal according to $L_{OF2}$. The FBG reflection signal per scan was identifiable even when $L_{OF2}$ varied. The reflection signals of FBG21 and FBG23 were constant because they were insensitive to $L_{OF2}$. The reflection signals of FBG22 varied proportionally to $L_{OF2}$, with a time variation of 9.8 ns per unit length variation of $L_{OF2}$. This was consistent with the propagation time per unit length of the optical fiber. These results indicate that pulse modulation allows to identify installations with arbitrary wavelength order over a wide range from 0 to 5050 m by using $L_{OF2}$, confirming its effectiveness for arbitrary installation of FBGs.

When real-time measurements are acquired using the buffered FDML laser for a distant FBG, a reflection signal is folded back to a sweep period of $19.7 \mu s \left(1/f_m\right)$. Therefore, we folded the results in Fig. 7(a) back over the sweep period, obtaining the results shown in Fig. 7(b). The FBG

![Fig. 7 Reflection signals by optical offset fiber $L_{OF2}$. (a) Reflection time with pulse modulation of three-buffered FDML laser. (b) Reflection time folded back at a sweep period.](https://www.spiedigitallibrary.org/journals/Optical-Engineering)
reflection signals folded back due to the change in $L_{OF2}$, and their change suitably agreed with the calculated value by the optical fiber length, indicating that our process is effective for identification at the time of folding. Therefore, during real-time measurement, this process can easily identify the detection order for reflection signal measurement. In Fig. 6(II-a) ($L_{OF2} = 1000$ m), the detection order is $\{t_{c_{c},23}^{(F1)}, t_{c_{c},21}^{(F1)}, t_{c_{c},23}^{(F2)}, t_{c_{c},21}^{(F2)}, t_{c_{c},23}^{(F3)}\}$ according to the results shown in Fig. 7(b). The reflection signal of each FBG was measured with both forward and backward scans. Therefore, in the reflection wavelength measurements of the FBG, the delay was corrected by determining the time difference between the FBG reflection signals obtained from the scans.33,38

Depending on length $L_{OF2}$, FBG reflection signals closer than 0.3 $\mu$s occurred. Consequently, the 3-nm occupied wavelength range of the FBG could not be secured, causing overlapping reflection signals. At $L_{OF2} = 1100$ m, overlapping occurred at six locations corresponding to $\{t_{c_{c},22}^{(F1)}, t_{c_{c},21}^{(F1)}, t_{c_{c},23}^{(F2)}, t_{c_{c},21}^{(F2)}, t_{c_{c},23}^{(F3)}\}$. Thus, pulse modulation allowed to identify both the FBG reflection signals and the overlapping sources.

The proposed measurement system implements an alert function to visualize overlapping based on identification by pulse modulation (Fig. 8). The occurrence of an alert is determined by the degree of proximity of the FBG reflection signals owing to pulse modulation. Therefore, when the system obtains a result for optical channel 2 with $L_{OF2} = 1100$ m, it automatically generates six alerts. The system also displays the alert source, with alert 1 (around 2.7 $\mu$s) indicating the occurrence of overlapping at $[t_{c_{c},22}^{(F1)}, t_{c_{c},21}^{(F1)}]$.

Figure 9 shows the reflection signals when alert 1 shown in Fig. 8 occurs. In Fig. 9(a), the reflection signals of $t_{c_{c},22}^{(F1)}$ and $t_{c_{c},21}^{(F1)}$ overlap, hindering their separation and demodulation. Figs. 9(b)–9(d) show the results of applying strain $\Delta \varepsilon_{22} = 100, 200$, and $300 \mu e$ to FBG22, respectively. With the application of strain, reflection signals $t_{c_{c},22}^{(F1)}$ of FBG22 were gradually separated.

As a slight change by strain or vibration can cause signal separation and assimilation, overlapping FBG reflection signals are difficult to demodulate in measurement systems. Therefore, the signal processing in Fig. 3, which shades a specific FBG, was implemented to solve overlapping. To prevent the occurrence of the six overlapping regions in Fig. 8, the FBGs must be shaded in any of the three switch patterns detailed in Table 2. Switch pattern SP1 shaded all backward scans ($B1, B2$, and $B3$) in the wavelength region of $\Delta \varepsilon_{22}$, eliminating alerts 1–3 shown in Fig. 8. In the buffered FDML laser, even if only $B1$ of the backward scan was shaded, $B2$ and $B3$ were also simultaneously shaded owing to triple multiplexing, thus shading all backward scans. In switch pattern SP1, all forward scans ($F1, F2$, and $F3$) in the wavelength region of $\Delta \varepsilon_{22}$ were also shaded to eliminate alerts 4–6.

Figure 10 shows the results of measuring the FBG reflection signals for each switch pattern indicated in Table 2. FBG22 was set at strain $\Delta \varepsilon_{22} = 200 \mu e$. Figure 10(I-a) shows reflection signals for $L_{OF2} = 1100$ m. Reflection signals overlapped in the time domain according to the

![Fig. 8 Screenshot showing overlap alerts ($L_{OF2} = 1100$ m).](image-url)
Six alerts shown in Fig. 8. Figures 10(I-b) and 10(I-c) show the magnified views in the periods where alerts 1 and 4 occurred. In both regions, reflection signals of two FBGs were close.

Figures 10(II)–10(IV) show the results of shading specific FBGs for switch patterns SP1, SP2, and SP3 (Table 2), respectively. In Fig. 10(II-a) for switch pattern SP1, all backward scans ($B_1, B_2$, and $B_3$) in the wavelength region of FBG$_{21}$ were shaded. Therefore, in Fig. 10(II-b) of alert 1, $t_{IC,21}^{(B_1)}$ was removed and only $t_{IC,22}^{(F_1)}$ was detected. In Fig. 10(II-a), all forward scans ($F_1, F_2$, and $F_3$) in the wavelength region of FBG$_{23}$ were shaded. In Fig. 10(II-c) of alert 4, $t_{IC,23}^{(F_1)}$ was removed and only $t_{IC,22}^{(B_1)}$ was detected. The processing of switch pattern SP1 confirmed that the reflection signals of one FBG was removed in the results of other alerts as well as in the results of alerts 1 and 4. By changing the FBG for shading with switch patterns, as shown in Figs. 10(III) and 10(IV), the reflection signal of the desired FBG could be shaded and

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**Table 2** Switch pattern for measuring overlapping FBG reflection signals at $L_{OF_2} = 1100$ m.

<table>
<thead>
<tr>
<th>FBG</th>
<th>FBG$_{21}$</th>
<th>FBG$_{22}$</th>
<th>FBG$_{23}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>1540</td>
<td>1550</td>
<td>1560</td>
</tr>
<tr>
<td>F/B</td>
<td>F</td>
<td>B</td>
<td>F</td>
</tr>
<tr>
<td>SP1</td>
<td>○</td>
<td>↓</td>
<td>○</td>
</tr>
<tr>
<td>SP2</td>
<td>○</td>
<td>○</td>
<td>↓</td>
</tr>
<tr>
<td>SP3</td>
<td>○</td>
<td>↓</td>
<td>○</td>
</tr>
</tbody>
</table>

Note: F: forward scan; B: backward scan; ○: switch on; and ↓, ↓: switch off.

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Fig. 9 Results of reflection signals when alert 1 occurs for $L_{OF_2} = 1100$ m under applied strain $\Delta \varepsilon_{22}$ of (a) 0; (b) 100; (c) 200; and (d) 300 $\mu$e.
acquired. By adjusting the switch pattern, only one FBG with overlapping reflection signals
could be detected, thus suppressing overlapping.

3.3 FBG Measurements with Measurement System

Strain measurements were performed using FBGs with multiple optical channels. To generate
strain, one end of an optical fiber of length $L = 1\text{ m}$ containing an FBG was attached to a fixed
stage, and the other end was attached to a movable stage (SGSP26-100, SIGMAKOKI). The
movable stage was moved along the longitudinal direction of the optical fiber by variation $\Delta X$
to stretch the optical fiber, and strain $\Delta \varepsilon = \Delta X / L$ was applied. To verify the effect of identifi-
cation and delay correction for FBGs in this experimental setup, $L_{OF1} = 1000\text{ m}$ was fixed and
$L_{OF2}$ was set to 0, 2000, and 5050 m. The length conditions did not cause overlapping reflection
signals between the FBGs. Figure 11 shows the strain measurements for each FBG and optical
channel. The reflection wavelength of each FBG changed to longer wavelengths in proportion to
the strain. The slope of the reflection wavelength with respect to strain was $1.2 \times 10^{-3}\text{ nm/\mu e}$
per FBG. Almost identical reflection wavelengths were obtained even for varying delays owing
to the installation distance via $L_{OF2}$. The difference between the measured values at $L_{OF2}$ of 2000
and 5050 m with $L_{OF2}$ of 0 m was below $5 \times 10^{-2}\text{ nm}$ for all FBGs. The standard deviation of the
reflection wavelength per FBG and optical channel was $< 9\text{ pm}$. These results indicate that the
proposed measurement system with the three-buffered FDML laser identifies and corrects
the delay of multiple FBG reflection signals and enables multichannel strain measurements with
FBGs over a wide installation range from 0 to 5050 m.

Fig. 10 Reflection signals with overlapping at $L_{OF2} = 1100\text{ m}$ (I) with three-buffered FDML laser
and switch patterns (II) SP1; (III) SP2; and (IV) SP3 for overlapping. (a) Reflection signals and their
magnified views around; (b) 2.7 $\mu$s (alert 1); and (c) 12.5 $\mu$s (alert 4).
Fig. 11 Strain measurements for each FBG and optical channels (I) 1 and (II) 2. Measurements for (I-a) FBG$_{11}$; (I-b) FBG$_{12}$; (I-c) FBG$_{13}$; (II-a) FBG$_{21}$; (II-b) FBG$_{22}$; and (II-c) FBG$_{23}$.

Fig. 12 Vibration measurements without overlapping for $L_{OF2} = 1000$ m in (a) FBG$_{21}$; (b) FBG$_{22}$; and (c) FBG$_{23}$.
Real-time vibration measurements were also performed using FBGs in optical channel 2. FBG$_{21}$ and FBG$_{23}$ were attached to bimorph piezoelectric transducers with vibration frequencies $f_{V21} = 4.46$ kHz and $f_{V23} = 2.12$ kHz, respectively. FBG$_{22}$ vibrated through a metal-shielded piezoelectric actuator with vibration frequency $f_{V22} = 20$ kHz. This experiment was conducted at $L_{OF2}$ of 1000 m without overlapping and 1100 m with overlapping. Figure 12 shows the vibration measurements without overlapping ($L_{OF2} = 1000$ m). Figures 12(a)–12(c) show the results for FBG$_{21}$, FBG$_{22}$, and FBG$_{23}$, respectively. The reflection wavelength of each FBG changed at each applied vibration frequency. The peak-to-peak values of the reflection wavelengths due to the vibration of each FBG were $\sim 0.13$, 0.15, and 0.13 nm, respectively. Without overlapping, as shown in Fig. 7(b), all reflection signals of each FBG were detected in the six forward and backward scans without signal proximity. In addition, the reflection wavelengths were calculated according to the order of detection of the FBG reflection signals identified by pulse modulation. The order of reflection wavelengths for FBG$_{21}$ was $t_{(B1)}^{(c, 21)}, t_{(F1)}^{(c, 21}), t_{(B2)}^{(c, 21)}, t_{(F2)}^{(c, 21)}, t_{(B3)}^{(c, 21)}, t_{(F3)}^{(c, 21)}$. The proposed measurement system using the three-buffered FDML laser achieved a time resolution of 3.3 $\mu$s ($1/6 f_m$).

The offset fiber was then changed to $L_{OF2} = 1100$ m, obtaining the vibration measurements with overlapping shown in Fig. 13. Overlapping was solved by applying switch pattern SP1 (Table 2). Figures 13(a)–13(c) show the results for FBG$_{21}$, FBG$_{22}$, and FBG$_{23}$, respectively. By shading the wavelength region of FBG reflection signals to eliminate overlapping, the reflection wavelength of each FBG could be demodulated. Each FBG had a sinusoidal wavelength variation at each vibration frequency, as in the results without overlapping (Fig. 12). Switch pattern SP1 shaded all backward scans ($B1, B2,$ and $B3$) in the wavelength region of FBG$_{21}$ and all forward scans ($F1, F2,$ and $F3$) in the wavelength region of FBG$_{23}$ to eliminate

![Fig. 13 Vibration measurements with overlapping for $L_{OF2} = 1100$ m in (a) FBG$_{21}$; (b) FBG$_{22}$; and (c) FBG$_{23}$.](image-url)
overlapping. For FBG21 in Fig. 13(a), the unshaded forward scans (F1, F2, and F3) had the reflection wavelengths demodulated. Similarly, for FBG23 in Fig. 13(c), only the unshaded backward scans (B1, B2, and B3) were demodulated for the reflection wavelengths. For FBG22 in Fig. 13(b), no shading was applied to the forward and backward scans, and the reflection wavelengths were demodulated in both scan directions (F1, F2, F3, B1, B2, and B3). The reflection wavelengths were calculated according to the order of detection of the FBG reflection signals shown in Fig. 7(b). The peak-to-peak values of the reflection wavelengths due to vibration of each FBG were ∼0.13, 0.16, and 0.13 nm, respectively, suitably agreeing with those shown in Fig. 12. FBG22 measured a higher vibration frequency of 20 kHz than the other FBGs. Therefore, any switch pattern indicated in Table 2 can be used to measure FBGs, but switch pattern SP1 allows to adjust the measurement to prioritize FBG22, which measures higher frequencies. Overall, these results demonstrate that shading the wavelength region of a specific FBG suppresses overlapping and enables real-time measurement of vibration with multiple FBGs.

3.4 Considerations for Measurement Systems with Buffered FDML Lasers

The method using buffered FDML lasers improves the measurement rate depending on the number of buffers. On the other hand, because this method involves multiplexing by extracting a portion of the wavelength-swept laser light, the sweep bandwidth is reduced. Therefore, the number of buffers should be adjusted considering the trade-off between laser sweep rate and sweep bandwidth. A two-buffered FDML laser has a sweep bandwidth of ∼39 nm, while the sweep rate is 202.8 kHz. Three-buffered FDML lasers have a sweep bandwidth of ∼28 nm and a sweep rate of 304.2 kHz. The maximum number of FBGs allowed depends on the sweep bandwidth of the laser and the wavelength range occupied by the FBGs. When the occupied wavelength range of FBGs is set to 5 nm to ensure a wide strain range, the maximum number of FBGs is 7 and 5 for the two- and three-buffered FDML lasers, respectively. For the high-speed multichannel detection of several FBG sensors, the peak detection speed must be improved. Our system achieves real-time peak detection by designing a peak detection process using an FPGA capable of digital arithmetic and parallel processing.

4 Conclusion

We introduce a measurement system that suppresses overlapping in multiple FBG reflection signals. The measurement system uses a three-buffered FDML laser with two channels, a measurement rate of 304.2 kHz and a sweep bandwidth of 28 nm. The measurement system uses laser pulse modulation to extract and identify reflection signals of FBGs placed at arbitrary distances. Furthermore, by using forward and backward laser scans, the reflection wavelength can be measured with delay compensation over a wide installation range. By identifying the reflection signals of all FBGs through pulse modulation, the overlapping signals are identified, generating an overlap alert in the system. To suppress overlapping, we shade the laser light in the wavelength region of one of the overlapping FBGs by an FSW. As a result, the measurement system suppresses reflection signal overlapping in FBGs placed at arbitrary distances and allows multichannel measurement of strain and vibration. This experiment has successfully measured the reflection wavelength of FBGs without any signal overlap. The measurement system at present prioritizes measuring all FBG wavelengths. Therefore, the measurement rate of FBGs excluded due to overlap is changing. In this regard, we will examine the possibility of frequency analysis using resampling and other techniques based on digital signal processing. In future work, we will improve the measurement system to handle higher sensor densities than the current setup.

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References


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