Multiplexed FBG-FFPI strainmeter array for field observation

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1. Introduction

Earthquake is a significant hazard and can potentially cause catastrophic disasters affecting humanity [1–8]. Mitigating the risk of earthquakes is a necessary and urgent task. Thus, earthquake early-warning has become a practical and essential approach to reduce the loss caused by large earthquakes [9–13]. Geological instruments such as creepmeter [14,15], tiltmeter, and strainmeter [16–19] are required for accurate earthquake early-warning. The strainmeter plays a unique role, as it can effectively record seismic waves and earth tides.

One promising approach to predict earthquakes is to mine the mass data of the earth's surface deformation gathered by strainmeters [20–23]. However, the large size and high cost of conventional strainmeters (e.g., alloy rods and laser interferometers [24,25]) pose limitations for their extensive deployment. Optical fiber sensors are becoming increasingly popular in geophysics due to their cost-effectiveness, high bandwidths, and immunity to electromagnetic interference. Recently, long baseline fiber strainmeters have been utilized for seismic detection [26–28] and observation of crustal deformation [29–31]. However, these strainmeters apply ultra-long fiber cables, making them challenging to deploy. Additionally, they can only provide in-line information over their fiber cable lengths. Thus, developing a short baseline strainmeter capable of collecting sufficient strain data on a larger scale has significant implications.

Fiber sensors based on fiber Bragg grating (FBG) [32,33] are good candidates for short baseline strainmeters because of their high integration, ease of installation, and particularly multiplexed operation. FBG-based fiber sensors include π-FBG sensors [34–37], FBG laser sensors [38–41], and FBG-based fiber Fabry-Perot interferometer (FBG-FFPI) sensors [42–44]. Among them, FBG-FFPI sensors exhibit high sensitivity due to comb-shaped reflective spectra. In addition, they can obtain an ultra-wide dynamic range by applying continuous jump-locking. Despite the advantages, it is still challenging to apply FBG-FFPI strainmeters for multiplexed field observation because FBG's reflective spectra are much broader than the tracking range of the Pound-Drever-Hall (PDH) technique [45].

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To solve this problem, Q. Liu et al. introduced time-domain multiplexed technology based on optical delay lines (ODL) for 3-channel strain sensing [46] and applied a multi-tone PDH technique based on optical frequency comb (OFC) for 2-channel strain sensing [47]. However, using ODL can cause an increase in fiber thermal noise, and OFC technology is too expensive. As a result, neither technique is suitable for on-site field observation.

This paper presents large-scale, ultrahigh-resolution, real-time multiplexed FBG-FFPI strainmeter arrays and deployment strategies for field observation using optical space-division multiplexing and electricity time-division multiplexing. We set up an FBG-FFPI strainmeter array with 10 channels at Lijiang National Seismic Station. Over a year, the array has recorded more than 100 earthquakes and the earth’s daily tide signal. In addition, we have also established a provisional 4-channel FBG-FFPI strainmeter array at Heqing Seismic Station for comparison. The results show that the multiplexed FBG-FFPI strainmeter arrays can provide numerous geophysical data for earthquake early-warnning.

2. Materials and methods

2.1. Working principle

The ultrahigh-resolution strainmeters rely on FBG-FFPIs written in polarization-maintaining (PM) fibers. The FBG-FFPI can produce a series of highly narrow spectral transmission peaks at the FBG’s reflection band by in-core Fabry-Perot (F-P) interference (refer to Fig. S1c). The PDH technique can lock a master and slave single-sideband (SSB) laser onto the corresponding FBG-FFPI resonance peaks for precise strain measurement. The feedback signal generated by the locking process is then used to extract sensing information (refer to Supplementary Information Section 1).

As shown in Fig. 1a, we utilize a strain-free FBG-FFPI (Ref. FFPI) as a temperature reference around the sensing FBG-FFPIs (Sen. FFPIs) to further improve the measurement accuracy. When there are fluctuations in temperature, the spectra of both the Ref. FFPI and Sen. FFPIs will shift synchronously. The master laser is locked onto the Ref. FFPI to eliminate frequency shifts caused by free-running laser instability. The SSB laser is generated by modulating the master laser using an SSB modulator. The SSB laser is locked onto the Sen. FFPIs to read out strain information. The master and SSB lasers’ track ranges are slightly wider than FBG-FFPIs’ free spectral range (FSR) to ensure that at least one resonance peak is obtained.

Fig. 1. (a) A strain-free Ref. FFPI is the temperature reference around the sensing Sen. FFPIs to further improve the measurement accuracy. (b) The initialization of the locking stage includes the standby and sweeping stages. In the locking stage, the feedback track voltage of the sensing loop will synchronize with the frequency shift caused by strain variation.

Fig. 2. (a) The setup of the multiplexed FBG-FFPI strainmeter array. (b) The deployment strategy for field observation.
As depicted in Fig. 1b, the initialization of the locking stage includes the standby and sweeping stages. Reflected light from each Sen. FFPI will sequentially pass through a multiplexer composed of a single-pole multi-throw (SPMT) switch array containing \(n\) switches, i.e., SW1, SW2, … and SWn. Only one channel’s (i.e., CH1, CH2, … CHn) signal can pass through the multiplexer at each query time. Once a valid signal is received, the corresponding channel will be activated from the standby to the sweeping stage. The error signal of the Sen. FFPI is then obtained by the sweeping stage, which can identify the error signal’s zero-crossing position and linear-zone slope. At last, the locking initialization will be finished, and the channel will be working in the locking stage (refer to Supplementary Information Section 2). In the locking stage, the feedback track voltage of the sensing loop will synchronize with the frequency shift caused by strain variation. Note that each channel’s working stage is independent. In addition, the reference and the sensing feedback loops are irrelevant.

2.2. System configuration

The setup of the multiplexed FBG-FFPI strainmeter array is shown in Fig. 2a. An industrial personal computer (IPC) is connected to a wavelength-tunable narrow-linewidth (<100 Hz) master laser (Koheras BASIK E15, NKT Photonics) and a field programmable gate array (FPGA, PCIe-7856R, National Instruments) to configure settings and store the sensing results. The master laser is modulated by a straight waveguide phase modulator (SPM, SPM-301A, PANWOO), driven by a signal generator (SG). The laser is then split into two beams by a 1:99 PM fiber coupler (CP). The beam with 1% power is directed into the Ref. FFPI through a PM circulator (CIR), while the beam with 99% power is modulated by an SSB modulator (KY-CS-SSB-15, KEYANG).

The SSB modulator is powered by a voltage-controlled oscillator (VCO, CVC055BE-1100-1600, CRYSSEK). The quadric frequency-shifted laser from the SSB modulator is split into ten beams using a 1x10 PM coupler. Each beam is then directed into a corresponding Sen. FFPI through a PM circulator (CIR), while the beam with 99% power is modulated by an SSB modulator (KY-CS-SSB-15, KEYANG).

The SSB modulator is powered by a voltage-controlled oscillator (VCO, CVC055BE-1100-1600, CRYSSEK). The quadric frequency-shifted laser from the SSB modulator is split into ten beams using a 1x10 PM coupler. Each beam is then directed into a corresponding Sen. FFPI through a PM circulator (CIR), while the beam with 99% power is modulated by an SSB modulator (KY-CS-SSB-15, KEYANG).

The quadric frequency-shifted laser from the SSB modulator is split into ten beams using a 1x10 PM coupler. Each beam is then directed into a corresponding Sen. FFPI through a PM circulator (CIR), while the beam with 99% power is modulated by an SSB modulator (KY-CS-SSB-15, KEYANG).

The SG produces a steady 60-MHz sine-wave directed into the demodulator’s 4×LO (local oscillator) port, while a 15-MHz sine-wave is used to operate the SPM. The FPGA processes the dual error signals and generates the closed-loop feedback voltage. Additionally, the FPGA can generate a burst pulse to coordinate the VCO and SPMT during a single query time (refer to Supplementary Information Section 3). A voltage conversion circuit (VoCC) converts the FPGA’s output voltage into tunable voltage for laser and VCO output signal regulation. The master laser, SPM, 1:99 CP, SSB, PDs, SPMT, demodulator, FPGA, VoCC, SG, and VCO comprise the interrogator.

The deployment strategy for field observation is shown in Fig. 2b. The FBG-FFPI array and SDMB are located in the observation cave. The FBG-FFPI array is installed on the bedrock or connecting platform. The fibers from the FBG-FFPI array are routed to the SDMB. Two 240-m long armored PM fiber cables and an armored multicore single-mode (SM) fiber cable connect the SDMB and interrogator through the cave entrance. The IPC and interrogator are situated in the instrument room.

3. Field observation at Lijiang National Seismic Station

Field observation was first conducted at Lijiang National Seismic Station, Yunnan Province, China. The strainmeter array was activated on June 10, 2021, and shut down on April 8, 2022.

3.1. Deployment strategy

The Sen. FFPIs have a central wavelength of 1549.87 nm and are pre-tensioned to ensure their working wavelength range overlaps with the Ref. FFPI’s 1550.24-nm central wavelength. All FBG-FFPIs have the same manufacturing parameters, i.e., 0.32-nm FBG bandwidth, 99.5% reflectivity, 3.68-μm FFPI FSR, 0.72-MHz FFPI FWHM, and 0.22-m cavity length. The reflective spectrum of a Sen. FFPI is shown in Fig. 3a.
The FFPI FSR is close to the voltage tunable range of the VCO, about 500 MHz, to ensure at least one peak is present during sweeping (refer to Fig. S2). The strain sensitivity of the FBG-FFPI is $306.94 \text{ n}\varepsilon/\text{V}$, as tested by a piezo nano-actuator. The control voltage of each channel can be read to calculate the real strain.

As shown in Fig. 3b, c (refer to Supplementary Information Section 4), each FBG-FFPI is directly mounted by fiber clamps on a pair of invar alloy pedestals for earthquake monitoring. The distance between two pedestals is designed to be 0.3 m, slightly longer than the cavity length of the FBG-FFPI. The alloy pedestals are fixed on a concrete platform using studs with nuts. The studs are vertically embedded into the concrete using grouting material but not anchored into the bedrock. The concrete platform is built on top of a bedrock.

Fig. 3d illustrates the distribution of the FBG-FFPI strainmeter array in the observation cave. The room’s dimensions are approximately 3\times9 m², containing three concrete platforms. The SDMB is positioned at the cave’s center, with the Ref. FFPI sensor placed on its top. The FBG-FFPI strainmeters are deployed as follows.

- CH0, CH3, CH4, CH5, and CH6 have north-south orientations.
- CH1, CH2, and CH9 have west-east orientations.
- CH7 has a northwest orientation.
- CH8 has a northeast orientation.

Please refer to Fig. 3e for a photo of the installation site of the FBG-FFPI strainmeter array.

3.2. Earthquake monitoring

The multiplexed FBG-FFPI strainmeter array system can effectively record the seismic signals of natural earthquakes during monitoring. For instance, on January 2, 2022, an ML = 5.5 earthquake (recorded by China Earthquake Networks Center, CENC) occurred in Ninglang, Yunnan Province, China, at 15:02:06. The epicenter coordinate is 27.79°N, 100.65°E, while the focal depth is 10 km. All FBG-FFPI strainmeters captured the seismic waves, including the primary, shake, and surface waves. The earthquake signal was detected at 15:02:24. Fig. 4 displays the waveforms of all channels after processing with an infinite impulse response (IIR) filter. The slight variations in magnitude among the FBG-FFPI strainmeters are attributed to the coupling efficiency between the pedestals and the concrete platform.

Fig. 4. The seismic waveforms after applying IIR filtering. On January 2, 2022, the ML = 5.5 earthquake occurred in Ninglang, Yunnan Province, China, at 15:02:06. The epicenter coordinate is 27.79°N, 100.65°E. The focal depth is 10 km.

The four orientations of different channels provide a complete vector of vibration information about the earthquake. The normalized seismic waves of the north-south orientated strainmeters (CH0, CH3, CH4, CH5, CH6), (b) west-east orientated strainmeters (CH1, CH2, CH9), (c) north-west orientated strainmeter (CH7), and north-east orientated strainmeter (CH8). (d) Comparison of the waveforms in orthogonal directions.

Fig. 5. The normalized seismic waves of the (a) north-south orientated strainmeters (CH0, CH3, CH4, CH5, CH6), (b) west-east orientated strainmeters (CH1, CH2, CH9), (c) north-west orientated strainmeter (CH7), and north-east orientated strainmeter (CH8). (d) Comparison of the waveforms in orthogonal directions.

The figures show that the waveforms of the same direction have the same phase.
Fig. 5c illustrates the waveform of the remaining two slanted directions, including northwest (CH7) and northeast (CH8). In addition, Fig. 5d compares the waveforms of orthogonal directions, i.e., east-west (CH2) and north-south (CH3). The waveforms of CH2 and CH3 exhibit opposite phases. As for CH7 and CH8, their waveforms have the same phases in certain regions but differ in others due to the non-strictly orthogonal deployment of these two channels. The waveforms of CH7 and CH8 can be synthesized from the east-west and north-south components.

The distance from the earthquake’s epicenter to the station can be estimated by calculating the time difference between the arrival of the primary (P-) and secondary (S-) waves. The P- and S-waves have a velocity difference of approximately 6–8 km/s. Fig. 6a displays an earthquake signal recorded by CH3. This earthquake occurred in Yangbi Yi autonomous county, Yunnan province, China, at 17:19:16 on October 20, 2021. The epicenter coordinate of the ML = 3.4 earthquake (recorded by CENC) is 25.73°N, 100.00°E, while the focal depth is 8 km. The arrival time difference of the P- and S-waves is approximately 18 s, and the estimated epicentral distance is 108–144 km.

Fig. 6b shows another earthquake signal recorded by CH3. This earthquake occurred in the Lao People’s Democratic Republic at 05:06:14 on December 20, 2021. The epicenter coordinate of the ML = 6.0 earthquake (recorded by CENC) is 19.60°N, 101.40°E, while the focal depth is 10 km. The arrival time difference of the P- and S-waves is approximately 105 s, and the estimated epicentral distance is 630–840 km.

In Fig. 6b, a small aftershock signal is also clearly recorded. Over a year, the multiplexed FBG-FFPI strainmeter array system has recorded over one hundred earthquakes. The epicenter coordinate of the farthest earthquake is in Peru (4.50°S, 76.70°W). The estimated epicentral distance of the ML = 7.3 earthquake is 17000 km (refer to Supplementary Information Section 5). The results show that the estimated epicentral distances are consistent with the data of CENC, proving the capability of the multiplexed FBG-FFPI strainmeter array system.

Fig. 6. Earthquake signal recorded by CH3. (a) An earthquake occurred in Yangbi Yi autonomous county, Yunnan province, China. (b) An earthquake occurred in Lao People’s Democratic Republic.

Fig. 7. The ultra-low frequency strain signals of CH3 and SS-Y from October 1 to October 11, 2021.

Fig. 8. Deployment strategy at Heqing Seismic Station. (a) The reflective spectrum of a Sen. FFPI. (b) and (c) shows the mounting strategy of invar alloy pedestals. (d) The distribution of the FBG-FFPI strainmeter array in the observation cave. (e) On-site picture.
3.3. Ultra-low frequency strain signal detection

Besides observing seismic activity, detecting ultra-low frequency strain signals below 1 mHz is essential. We installed a conventional 30-m SS-Y extensometer in the east-west orientation at the entrance of the observation cave for comparison. The ultra-low frequency strain signals of CH3 and SS-Y from October 1 to October 11, 2021, are shown in Fig. 7. The CH3 has been down-sampled to match the sample rate of SS-Y. The FBG-FFPI strainmeter array and SS-Y exhibit a signal period of approximately 24 hours with semi-diurnal variation. We attribute the signal to the earth's tide signal (refer to Supplementary Information Section 6).

The strain power spectral densities (PSDs) of the channel outputs over 40 minutes are plotted in Fig. 8. The resolutions of all channels are better than 10 $\mu$ε/√Hz for frequencies higher than 1 Hz, which is limited by the thermal noise of the VCO. The standard deviation of the short-term fluctuation is approximately 28.6 $\mu$ε (refer to Supplementary Information Section 7).

4. Provisional field observation at Heqing Seismic Station

A provisional field observation was conducted at Heqing Seismic Station in Yunnan Province, China. The system operation started on March 14, 2022, and concluded on March 26, 2022.

4.1. Deployment strategy

More precise FBG-FFPIs were used to achieve more sensitive field observation at Heqing Seismic Station. All FBG-FFPIs have the same manufacturing parameters, i.e., 0.4-nm FBG bandwidth, 99.5% reflectivity, 0.781-μm FFPI FSR, 0.25-MHz FFPI FWHM, and 1.4-m cavity length. The VCO powering the SSB modulator in Fig. 2 is replaced by CVCO55CL-0805-0900, CRYSTEK. The VCO’s tuning range is 95 MHz. The reflective spectrum of a Sen. FFPI is shown in Fig. 8a. The strain sensitivity of each FBG-FFPI was tested using a piezo nano-actuator and found to be 34.17 $\mu$ε/V.

Due to the longer cavity length of the FBG-FFPIs, we redesigned the invar alloy pedestal to ensure proper coupling with the bedrock. As shown in Fig. 8b,c (refer to Supplementary Information Section 8), an invar alloy pedestal consists of a long pillar, an auxiliary platform, a bracket, and three fiber clamps.

![Fig. 9. (a) The seismic waveforms after applying IIR filtering. On March 16, 2022, the ML = 7.4 earthquake struck Namie, Fukushima, Japan, at 22:36:29. The epicenter coordinate is 37.65°N, 141.95°E. The focal depth is 63 km. (b) Zoomed-in waveform.](image)

![Fig. 10. (a) Seismic waveform recorded by the two stations. On March 23, 2022, the ML = 6.6 earthquake occurred in Taidong, Taiwan province, China. The epicenter coordinate is 37.65°N, 141.95°E. The focal depth is 63 km. (b) shows PSD of the two stations.](image)
The long pillar is vertically embedded into the concrete using grouting material and anchored into the bedrock. The bracket secures the auxiliary platform on the long pillar. Three fiber clamps are placed on the auxiliary platform at 45° intervals from each other to enable sensing of different orientations. Fig. 8d,e displays the distribution of the FBG-FFPI strainmeter array in the observation cave. Four pedestals are installed at the vertices of a square with a side length of 1.6 m. Each FBG-FFPI is directly mounted by fiber clamps on a pair of invar alloy pedestals for earthquake monitoring. The FBG-FFPI strainmeters are deployed as follows:

- CH0 has a west-east orientation.
- CH1 has a north-south orientation.
- CH2 has a northeast orientation.
- CH3 has a northwest orientation.

4.2. Earthquake monitoring

On March 16, 2022, an ML = 7.4 earthquake struck Nami, Fukushima, Japan, at 22:36:29 (recorded by CENC). The epicenter coordinate is 37.65°N, 141.95°E, while the focal depth is 63 km. This earthquake was preceded by an ML = 6.0 foreshock at 22:34:22. Fig. 9a displays the seismic waveforms after applying infinite impulse response (IIR) filtering (refer to Supplementary Information Section 9 for the original data). The figure illustrates a distinct signal of a small foreshock closely followed by a significant earthquake, with a time interval of 127 s (refer to Fig. S8). The FBG-FFPI strainmeter array exhibits better response consistency than the Lijiang National Seismic Station one because of improved sensitivity. Fig. 9b presents a detailed waveform.

4.3. Comparison of field observation in two seismic stations

We compared recorded earthquakes from both seismic stations. On March 23, 2022, an ML = 6.6 earthquake occurred in Taidong Taiwan province, China (recorded by CENC). The epicenter coordinate is 23.45°N, 121.55°E, while the focal depth is 20 km. Fig. 10a shows the seismic waveform recorded by the two stations. Because of the different epicentral distances (2175.82 km for Lijiang National Seismic Station and 2180.50 km for Heqing Seismic Station), the arrival time interval at the two stations is approximately 4.85 s. Fig. 10b shows the PSD of the two stations. The resolution of the FBG-FFPI strainmeter array at Heqing Seismic Station is above 1 p√Hz when the frequency is > 10 Hz. The array at Heqing Seismic Station has a resolution of 4.80 p√Hz @ 30 Hz, while the one at Lijiang National Seismic Station has a resolution of 476 fs√Hz @ 30 Hz.

5. Conclusion

This paper presents the development and deployment of large-scale, ultrahigh-resolution, real-time multiplexed FBG-FFPI strainmeter arrays for field observation. The strainmeters rely on FBG-FFPIs written in PM fibers, which produce highly narrow spectral transmission peaks through in-core F-P interference. The PDH technique locks the master and slave SSB lasers onto the FBG-FFPI resonance peaks for precise strain measurement. 10-channel and 4-channel multiplexed FBG-FFPI strainmeter arrays have been successfully deployed at Lijiang National Seismic Station and Heqing Seismic Station, respectively. The arrays have recorded numerous seismic and ultra-low frequency strain signals. The recorded data demonstrate the effectiveness of the multiplexed FBG-FFPI strainmeter arrays in providing geophysical data for earthquake early-warning. This research contributes to developing cost-effective and high-resolution strainmeters for earthquake monitoring and mitigation.

CRediT authorship contribution statement

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Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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