Distributed Vibration Sensing of Seismic Event by Optical Frequency Domain Reflectometry

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Abstract *We measured a seismic event with OFDR. OFDR together with the unique feature of adjusting the measurement performance was used to analyse the event from different perspectives, and it could also be useful for revealing the features of infrequent seismic events.*

Introduction

Distributed vibration sensing (DVS), which is one application of optical fibre reflectometry that measures backscattered light along optical fibre, measures dynamic strain by detecting temporal variations in backscattered light[1]. Each location along the sensing fibre works as a strain sensor to achieve distributed measurement. This measurement is a unique feature of DVS, and DVS is used for surveillance in large-scale facilities[2].

One application field is investigating seismic events. Utilizing an installed optical telecommunication fibre as a sensing fibre, DVS has demonstrated the capability of measuring a seismic event continuously along the sensing fibre[3]–[5]. Moreover, dynamic strain distribution has revealed undiscovered geologic structures[6],[7]. Thus, DVS is a new tool for exploring geophysics.

DVS for seismic events currently adopts the method of optical time domain reflectometry, which launches an optical probe pulse into the sensing fibre and detects backscattered light[8]–[10]. The spatial resolution, which is given by the probe pulse width, and distance range are in a trade-off relationship due to the signal-to-noise ratio of backscattered light from the sensing fibre. The measurement conditions determine the measurement performance with respect to distance. The determined measurement performance may miss features of infrequent seismic events.

In this work, we adopt optical frequency domain reflectometry (OFDR) with the unique feature of measurement performance adjustment, and we demonstrate DVS for a seismic event. To the best of our knowledge, this is the first time that a seismic event has been detected by OFDR. The seismic event that occurred was an earthquake with a small enough amplitude that people did not feel the event, and the sensing fibre used was a standard telecommunication fibre installed in a model simulating an optical fibre network including telecommunications outside plants not optimized for seismic event

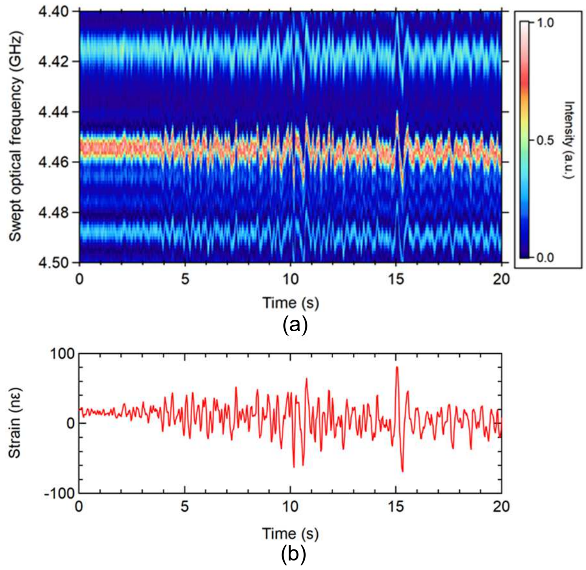

Fig. 1: Example of DVS by OFDR. (a) Optical spectrogram of Rayleigh backscattered light. (b) Strain waveform.

measurement. We adjusted the spatial resolution, which is in a trade-off relationship with sensitivity, to investigate the seismic event with the installed telecommunication fibre. Different features of the seismic event were revealed depending on the different measurement performance.

Experiment

OFDR, which launches optical frequency-swept probe light, can measure an optical spectrum of Rayleigh backscattered light at each location along a sensing fibre by using a Fourier transform[11]. Since the optical spectrum of Rayleigh backscattered light shows a spectral shift proportional to strain whose proportional coefficient is 151 MHz/$\mu\varepsilon$ for a wavelength of 1550 nm[12], analysing the spectral shift in an optical spectrogram reveals the dynamic strain[13]. The window length for the Fourier transform and optical frequency resolution are in an inverse proportion, so the spatial resolution for strain and the sensitivity for the spectral shift or strain are in the same relationship, and a

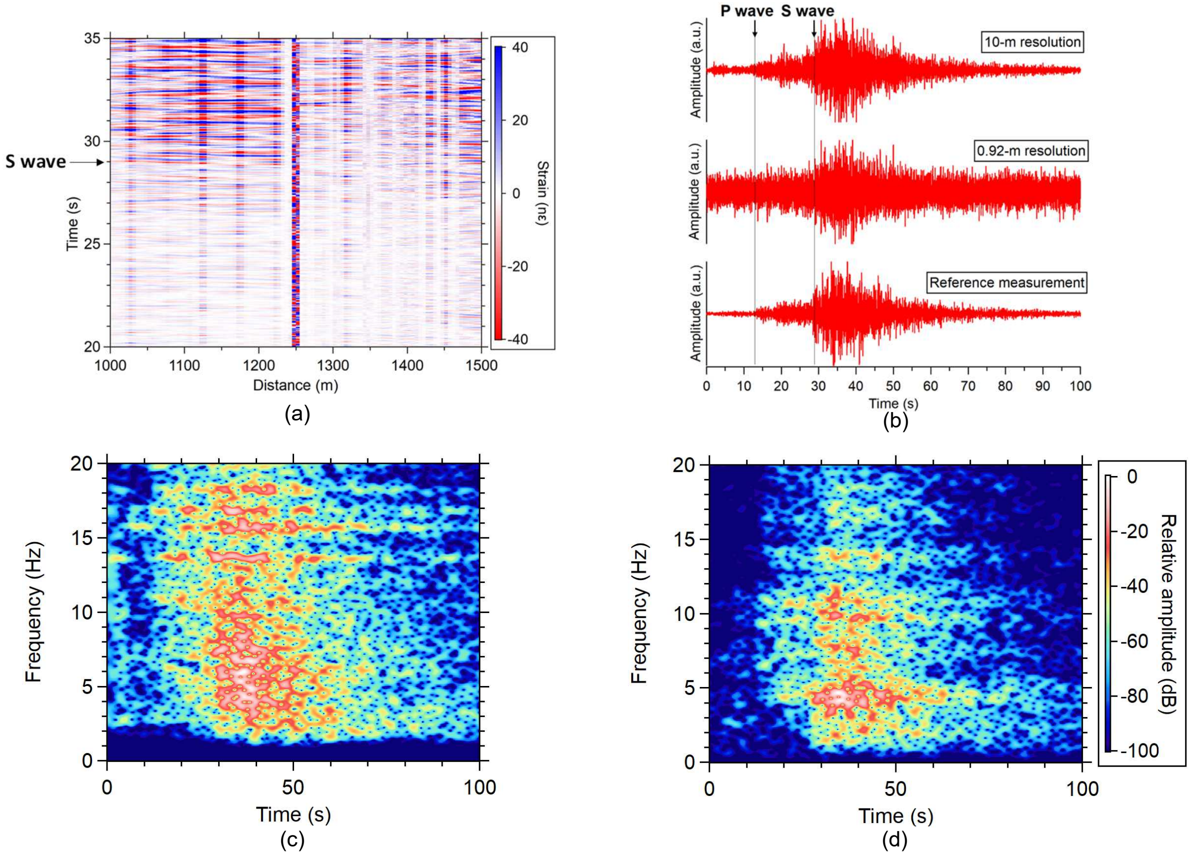

Fig. 2: Seismic-event measurement results. (a) DVS result. (b) Temporal vibration waveforms with DVS and vibration meter. Spectrograms with (c) 10-m spatial resolution and (d) vibration meter. “P wave” and “S wave” represent arrival time of each wave.

longer spatial resolution has a better strain sensitivity. Fig. 1 shows an example of an optical spectrogram for the seismic event and analysed dynamic strain with a spatial resolution of 10 m. As can be seen, the seismic event induced a spectral shift, or dynamic strain, from a time of 4 s. Analysing the optical spectrogram at each location along the sensing fibre makes it possible to construct a distributed vibration waveform.

We utilized one standard G.652 optical fibre inside a telecommunication cable deployed on the premises of our laboratory for seismic event detection. The total length of the fibre was limited to 1.6 km due to the size of the premises. The cable route consisted of a first section of 200 m inside the laboratory building, an outside second section of 300 m from east to west, then 1000 m from southeast to northwest, and, finally, 100 m from east to west. The outside section of the cable was installed in a buried conduit. The fibre was installed in a model simulating telecommunications outside plants such as manholes and closures and was not optimized for measuring seismic events like a direct buried fibre that makes direct contact with the ground and measures a seismic waveform with fidelity[5]. Since telecommunications outside plants protect cables against disasters so that uninterrupted telecommunications service can be provided, the installed fibre in this demonstration had less sensitivity to seismic events.

We adopted a customized OFDR to measure the seismic event[14]. The OFDR had two features compared with the conventional OFDR. One was an external single side band modulation of high coherence seed light for generating frequency-swept probe light[15], and this technique improves the measurement range and repetition rate of probe light, that is, the temporal sampling rate. The other is a relative distance measurement scheme that investigates an arbitrarily distant location by giving a distance offset to the measurement range[14]. These features overcome the drawbacks of OFDR, that is, a short measurement range and low temporal sampling rate, and will expand the application field including DVS. The measurement setup had a probe light bandwidth of 5.4 GHz, a repetition rate of 400 Hz, and a delay fibre length of 2500 m to investigate locations centering around 1250 m of the installed optical fibre. We used a vibration meter installed at the laboratory building for reference measurement.

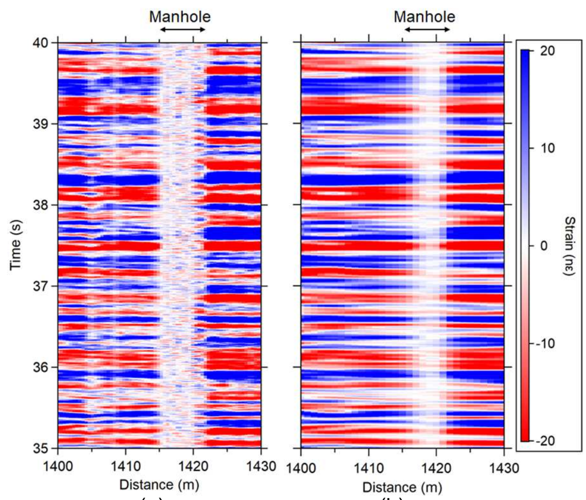

Fig. 3: DVS results around manhole with spatial resolutions of (a) 0.92 m and (b) 10 m.

We adopted two spatial resolutions, 10 m and 0.92 m, to analyse the seismic event.

First, we discuss the measurement results obtained with the spatial resolution of 10 m, which emphasizes strain sensitivity. Fig. 2(a) shows a measurement result obtained along a distance of 1000 to 1500 m for the seismic event, whose magnitude was 4.1, and the epicentre was on the Fukushima coast, 130 km northeast from Tsukuba. Emphasizing the strain sensitivity made it possible to clearly capture the dynamic strain for the seismic event, which had a small amplitude that people did not feel it, despite the fact that the sensing fibre was deployed in an optical fibre network. The measurement result included non-negligible noise around 1250 m, and the noise came from a DC beat frequency spectrum larger than Rayleigh backscattered light. The dynamic strain had an inconsistent amplitude along the fibre path, and responses to the ground motion differed depending on the location. The sensing fibre in this demonstration was not an optimized one that makes direct contact with the ground along the fibre path, and the difference in interaction depending on the location with the ground motion caused the inconsistent amplitude. A comparison between DVS and a reference measurement is shown in Fig. 2(b)-(d). Here, the DVS temporal waveforms were a second derivative with respect to time and had the same dimensions as the reference measurement with dimensions of acceleration. In Fig. 2(b), a 10-m resolution captured an entire temporal waveform including P and S waves, but a sub-1-m resolution captured a S wave due to the insufficient strain sensitivity. The two results of the 10-m resolution and reference measurement had a slight difference because the sensing fibre in this experiment detected vibration including the frequency response characteristic of the installation conditions. Comparing Figs. 2(c) and (d), for example, a frequency of 14 Hz becomes noticeable due to the installation condition compared with the reference measurement, but the two results are almost in agreement.

Next, we focused on a fine spatial resolution. Fig. 3 shows a comparison between the results obtained with the spatial resolutions of 0.92 m and 10 m. The distance range was around a manhole that the sensing fibre cable was passed through without ground contact. Prior to measuring the seismic event, we confirmed that the distance along the optical fibre path corresponded to the location of the manhole by detecting an identification vibration signal with DVS[16]. The spatial resolution of 10 m showed continuous distributed vibration along the fibre due to the insufficient resolution, and spatial blurring hampered the identification of the manhole location. In comparison, the sub-1-m resolution showed discontinuous distributed vibration. This is reasonable because the sensing fibre cable, which did not make contact with the ground, was thus insensitive to ground motion. This demonstration utilized an optical fibre installed in an optical fibre network as a sensing fibre and therefore identifies telecommunications outside plants. In the case of applying the technique for geophysics, a better spatial resolution than that of OTDR would also be useful for visualizing geologic structures in detail and could lead to new findings.

Conclusion

We demonstrated seismic event measurement with OFDR. The unique feature of adjusting the measurement performance to emphasize either sensitivity or spatial resolution provided different aspects of the event. We utilized a standard telecommunication optical fibre incorporated in optical fibre network as a sensing fibre, which was not designed for seismic event measurement, and successfully measured a seismic event with a small amplitude. Emphasizing sensitivity with a coarse spatial resolution of 10 m captured the entire temporal waveform, while a fine spatial resolution of sub-1-m captured only S wave. However, this fine spatial resolution visualized differences in the geologic structure of a manhole. Adjusting the measurement performance can be useful for analysing infrequent seismic events from different perspectives, and OFDR can be a new instrument for investigating geophysics.

References

[1] X. Bao *et al.*, “Recent development in the distributed fiber optic acoustic and ultrasonic detection,” *IEEE J. Lightw. Technol.,* vol. 35, no. 16, pp. 3256-3267, Sep. 2016.

[2] A. Owen and G. Duckworth, “OptaSense: Fiber optic distributed acoustic sensing for border monitoring,” in *Proc. Intell. Security Inform. Conf.*, 2012, pp. 362-364.

[3] N. J. Lindsey *et al.*, “Fiber-optic network observations of earthquake wavefields,” *Geophs. Res. Lett.*, vol. 44, no. 11, pp. 11792-11799, Dec. 2017.

[4] E. F. Williams et al., “Distributed sensing of microseisms and teleseisms with sub marine dark fibers,” *Nat, Commun.*, vol. 10, 5778, Dec. 2019.

[5] J. B. Ajo-Franklin et al., “Distributed acoustic sensing using dark fiber for near-surface characterization and broadband seismic event detection,” *Sci. Rep.*, vol. 9, 1328, Feb. 2019.

[6] P. Jousset *et al.*, “Dynamic strain determination using fibre-optic cables allows imaging of seismological and structural features,” *Nat. Commun.*, vol. 9, 2509, Jul. 2018

[7] N. J. Lindsey et al., “Illuminating seafloor faults and ocean dynamics with dark fiber distributed acoustic sensing,” Science, vol. 366, 6469, pp. 1103-1107, Nov. 2019.

[8] R. Posey Jr. *et al.*, “Strain sensing based on coherent Rayleigh scattering in an optical fibre,” *Electron. Lett.*, vol. 36, no. 20, pp. 1688-1689, Sep. 2000.

[9] A. Masoudi *et al.*, “A distributed optical fibre dynamic strain sensor based on phase-OTDR,” *Meas. Sci. Technol.*, vol. 24, no. 8, p. 085204, Jul. 2013.

[10] J. Pastor-Graells *et al.*, “Single-shot distributed temperature and strain tracking using direct detection phase-sensitive OTDR with chirped pulses,” *Opt. Exp.*, vol. 24, no. 12, pp. 13121-13133, 2016.

[11] M. Froggatt and J. Moore, “High-spatial-resolution distributed strain measurement in optical fiber with Rayleigh scatter,” *Appl. Opt.*, vol. 37, no. 10, pp. 1735-1740, 1998.

[12] Y. Koyamada *et al.*, “Fiber-optic distributed strain and temperature sensing with very high measurand resolution over long range using coherent OTDR,” *IEEE J. Lightw. Technol.*, vol. 27, no. 9, pp. 1142-1146, May 2009.

[13] D. P. Zhou *et al.*, “Distributed vibration sensing with time-resolved optical frequency-domain reflectometry,” *Opt. Exp.*, vol. 20, no. 12, pp. 13138–13145, 2012.

[14] T. Okamoto *et al.*, “Identification of sagging aerial cable section by distributed vibration sensing based on OFDR,” in *Proc. Optical Fiber Communication Conference (OFC) 2019*, paper Th2A.26.

[15] Y. Koshikiya *et al.*, “Long range and cm-level spatial resolution measurement using coherent optical frequency domain reflectometry with SSB-SC modulator and narrow linewidth fiber laser,” *IEEE J. Lightw. Technol.*, vol. 26, no. 18, pp. 3287-3294, Sep. 2008.

[16] D. Iida *et al.*, “Advances in distributed vibration sensing for optical communication fiber state visualization,” *Optical Fiber Technol.*, vol. 57, 102263, 2020.