A Signal Processing Algorithm Proposed for OFDR Distributed Sensing System to Enhance Its Performance

Bingjian Li¹, Jiwen Cui², Xuping Zhang³, Hong Dang², Xun Sun², Dong Jiang⁴, and Kunpeng Feng³,a

¹Shandong Aerospace Electro-technology Institute, Yantai, 264670 China
²Center of Ultra-Precision Optoelectronic Instruments, Harbin Institute of Technology, Harbin 150080, China
³Institute of Optical Communication Engineering, College of Engineering and Applied Sciences, Nanjing University, Nanjing 210093, China
⁴Huawei Technologies Co. Ltd., Beijing 100085, China
ᵃCorresponding author’s e-mail: kpfeng@nju.edu.cn

Abstract. A novel OFDR processing algorithm is proposed to improve the measurable range. The high local similarity found between the reference and measurement Rayleigh scattering spectrum (ReS and MeS). The spectrum shift of the Rayleigh backscatter which is the function of strain is measured using an improved optical frequency-domain reflectometry (OFDR). This method is improved by matching local ReS on MeS rather than a direct cross-correlation between whole ReS and MeS in conventional OFDR methods. By this method, a larger measurable range (0~3000µε) OFDR method with a high level spatial resolution (3mm gauge) is experimentally achieved comparing to conventional OFDR methods.

1. Introduction
Optical fiber distributed sensors (OFDS) show high potential in the fields of structural health monitoring, radiation detecting, reconstruction of 3-dimensional (3D) shape and pipeline surveillance, for their capability of carrying high dense information along a single fiber, being immune to electromagnetic interference, and high spatial and spectrum resolution [1-5]. OFDS have completed the transition from quasi-distributed to real-distributed sensing over the past 20 years with the development of the intrinsic backscattering light in optical fiber [1]. Among OFDS of different measuring principles, optical frequency domain reflectometer (OFDR) based on intrinsic Rayleigh scattering (RS) has been given tremendous attention as a result of its high spatial and spectrum resolution and without sensing dead-zone.

Theoretically, there is no dead zone in this method which could achieve a spatial resolution of mm-level. However, in practice, the measurement accuracy of distributed strain and the feasibility is limited by the similarity between reference RS spectrum (known strain distributed) and measurement RS spectrum. Furthermore, the similarity would quickly degenerate when the loaded strain is larger than 1000 µε and the sensing spatial resolution is high [6, 7]. With the similarity degeneration, fake or multi-peaks begin to appear in the cross-correlation results which would induce mistakes in spectrum shift calculating. Therefore, OFDR based on RS fingerprint spectrum which can measure a strain larger than 1000 µε was rarely reported, especially under a spatial resolution of mm-level.
In this paper, a novel OFDR processing algorithm for a large range OFDR method under a high spatial resolution of mm-level is proposed. The high similarity of local RS fingerprint spectrum is discovered and investigated in this letter. By matching RS local fingerprint spectrum, the spectrum shift is obtained with a better cross-correlation result between the reference local spectrum and the corresponding measurement local spectrum, so that the OFDR performance under a large strain is greatly enhanced. As the result, SNR of cross-correlation is improved, meanwhile, mistaken spectrum shifts caused by fake peaks and multi-peaks can be thoroughly controlled. Distributed Rayleigh backscatter spectrum is measured through OFDR technique, which will be changed by any ambient temperature or strain variations. By calculating the spectrum shifts between the Rayleigh backscatter spectrum data from each fiber gauge under a distributed strain load and unstressed states, distributed strain shifts can be obtained. A specific function could be achieved for strain discrimination by fitting spectrum shifts and strain shifts. Experimental results indicate that a largest distributed strain up to 3000 µε (limited by maximum load of strain distributed of fiber) with a highest spatial resolution downwards to 3 mm can be achieved. The nonlinearity is less than 0.5%.

2. Sensing Principle
Rayleigh scattering is an intrinsic property due to the irregular refractive index distributed of an optical fiber and can be equally equivalent to a random weak grating. The refractive index distributed, just like “fingerprint”, is stable and unique once SMF is manufactured. As FBG spectrum will be shift by strain, the external strain also causes Rayleigh scattering spectrum shift. The ratio of spectrum shift versus strain is constant for a specific fiber. Thus, strain sensing can be achieved by monitoring Rayleigh scattering spectrum shifts.

OFDR technics are used to monitor Rayleigh scattering spectrum. OFDR converts the interference between reference swept laser and RS along the SMF, into signals of different frequency. In conventional OFDR methods, the fast Fourier transformation (FFT) is used to process OFDR signals for transforming the wavelength domain (time domain) of the optical frequency domain signal to the distance domain (frequency domain). Also, the light spectrum information at different certain positions can be obtained. The short-time Fourier transformation (STFT) is used to extract certain position’s light information and transform signal into spectrum domain, wherein window center and bandwidth respectively represent the position and spatial resolution. The data length of fiber gauges is determined by spatial resolution and represents the distance length of extracted information used for a certain point’s strain calculation. Through moving STFT window, RS spectrum of each local fiber gauges along the SMF are serially calculated with a constant moving interval. The strain distributed of reference OFDR signal is known. Thus, strain is obtained by comparing the RS spectrum shift between the reference and measurement OFDR signal at the certain position.

![Figure 1. Schematic of spectrum shift between MeS and ReS.](image)

Theoretically, RS spectrum of a local fiber gauge has a high similarity between reference spectrum and measurement spectrum. Cross-correlation would have a high SNR and a single peak representing spectrum shift is much higher than other noise peaks [8]. Thus, cross-correlation is used to obtain the spectrum shift in conventional OFDR methods. In practice, however, this property only works fine when the loaded strain is below 1000 µε. That is mainly due to the spectrum shift caused by the loaded strain. As you can see in the figure 1, the strain will introduce new spectrum to the certain position’s extracted measurement spectrum information. With the increasing of the loaded strain, the proportion of new RS spectrum increases and the similarity between the whole measurement and reference
spectrum degenerates. In this case, SNR of cross-correlation may decrease, at the same time, amplitudes of noise peaks raise and have similar height with the peak representing spectrum shift, which is called multi-peaks. Furthermore, some could be higher than the true peak, also called fake peaks. Because of the fake peaks or multi-peaks, the calculating of spectrum shift becomes inaccurate especially when the loaded strain is larger than 1000 µε. The strain measurable range of OFDR is thus limited.

Figure 2. Comparison between whole spectrum (WS) and local spectrum (LS). WRS: whole reference Rayleigh scattering spectrum; WMS: whole measurement Rayleigh scattering spectrum; LRS: local reference Rayleigh scattering spectrum; LMS: local measurement Rayleigh scattering spectrum.

Figure 2 shows the MeS (under 1000 µε) and ReS (with no strain). Spatial resolution of this experiment is set at 3mm. As you can see when a large strain is loaded, the similarity between the matched spectrum sections of reference spectrum (solid blue lines) and measurement spectrum (solid purple lines) is higher than whole ReS (dotted blue line) and MeS (dotted purple lines) apparently. Also, a fake peak was founded in the whole spectrum cross-correlation result even the applied strain was just 1000 µε, as shown in Figure 3. Thus, it is difficult to determine spectrum shift through the cross-correlation result of the whole spectrum. Controlling influences of fake or multi peaks is essential for OFDR to extend measurable strain range. However, the cross-correlation of local ReS and MeS has a single and strong peak. That helps control influences cause by similarity degeneration and makes the calculation of spectrum shifts easy. And it can be used to improve the OFDR performance.

Figure 3. Comparison between LS and WS of cross-correlation results.

An improved OFDR processing algorithm proposed in this letter for strain discrimination is as follows. Strain shift is calculated by local spectrum matching.

1) Sample OFDR signal $S_r(t)$ in a SMF under unstressed status and save it as the reference Rayleigh scattering spectrum.
2) Select a proper fiber gauge length which represents spatial resolution and step length which should be smaller than 0.5 fiber gauge length.
3) FFT of reference OFDR signal $S_r(t)$ into distance domain signal $R_r(l)$ via FFT.
4) Extract $i_\lambda$ certain position’s signal data $R_r(l)$, wherein data length of light information is determined by the fiber gauge length and data position is calculated by $i \times \text{steplength}$
5. Add zero to $R_r(l)$ for offsetting the loss of spectral resolution. The zero number is determined by selected spectrum resolution. The spectrum resolution is calculated by dividing experiments’ light spectrum range by the data $Z_r(l)$ length which consists zero array and $R_r(l)$.

6. IFFT of $Z_r(l)$ into spectrum domain and get the whole reference spectrum $WRS_i$ of the $i$th fiber gauges via STFT.

7. Save the 24% part located in the middle of each $WRS_i$ as a local reference spectrum $LRS_i$.

8. Sample OFDR signal $S_m(t)$ under with a known distributed strain (not 0 $\mu\epsilon$) as the measurement Rayleigh scattering spectrum.

9. Transform measurement OFDR signal $S_m(t)$ into distance domain via FFT.

10. Extract certain position’s signal data $R_m(l)$.

11. Add zero to $R_m(l)$ for offsetting the loss of spectral resolution which is caused by the STFT.

12. Transform $Z_m(l)$ into spectrum domain and get the whole measurement spectrum $WMS_i$ of the $i$th fiber gauges via STFT.

13. Match the local reference spectrum $LRS_i$ on local the measurement spectrum $LMS_i$ within the whole measurement spectrum $WMS_i$ based on residual sum of squares results of local similarity, as shown in (2). The residual sum of squares of matched $LMS_i$ is minimum [9, 10].

14. Calculate the horizontal coordinate $x_i$ of the matched local MeS by centroid algorithm.

$$x_i = \frac{\sum k_j j_i}{\sum j_i}$$

where, $k_i$ is the $i$th horizontal coordinate; $j_i$ is the $i$th residual sum of squares between normalized local ReS and MeS.

15. Calculate spectrum shift $\Delta \lambda$ by comparing horizontal coordinates of the matched local ReS and MeS.

16. Calculate the corresponding $\Delta \epsilon$ using the linear function between spectrum shifts and strain shifts.

17. Repeat the process form (8) to (16) and complete a whole fiber’s strain discrimination. Figure 4 shows the flow diagram of the improved OFDR processing algorithm utilizing high local spectrum similarity.

Figure 4. The flow diagram of OFDR distributed sensing based on local similar characters of RS spectrum.

3. Experiments and Discussion

The experimental setup is set up as current OFDR systems, which is shown in Figure 6 [11, 12]. The balanced photodetector (BPD) in this OFDR system is a Thorlabs polarization dependent balanced detector (INT-POL-1550). DAQ is an Advantech data sampling card (PCI-1714). The OFDR
configuration consists of a Yenista external cavity tunable laser source (Tunics Reference) operating around 1550 nm with a continuous sweep mode. During the experiments, the sweep rate, center wavelength and tunable range is set at 40nm/s, 1550 nm and 10 nm respectively. When the laser is tuned, the couplers are used for the extraction of a portion of the light from the laser for three modules: (1) the wavelength calibration module; (2) the auxiliary interferometer module; (3) the measurement interferometer module.

![Diagram of OFDR distributed sensing system and experimental setups.](image)

Figure 5. Schematic of OFDR distributed sensing system and experimental setups. OFDR: optical frequency-domain reflectometry; TLS: tunable laser source; OC: optical coupler; DAQ: data acquisition; PBS: polarization beam splitter; BPD: Balance photodetector; FUT: fiber under test. Bottom inset shows the sensing fiber section, where a 0.4 m long fiber could be applied axial strain by attaching the fiber on the stepper motorized stage.

Experimental results of average similarity of two algorithms with different spatial resolutions (3 mm, 5 mm, 10 mm and 20 mm length) under loaded distributed strains from 1000 to 3000 µε are compared in Figure 6. When large strain is loaded, no matter what the spatial resolution is selected, the spectrum average similarities of conventional algorithm (dotted lines) are below 0.2. It is hard to determine the true spectrum shifts in this situation. The main reason for similarity degeneration is large spectrum shifts caused by large distributed strain. So a new algorithm utilizing high local spectrum similarity is proposed to help spectrum shifts calculation. The proposed algorithm (solid lines) in Figure 6 achieves ~0.8 normalized similarity under a distributed strain ranging from 1000 to 3000 µε with a 3 mm long fiber gauge, is about quadruple as the conventional algorithm. In practice, the similarity between ReS and MeS is significantly improved by the local spectrum of high similarity proposed and investigated in this paper.

![Diagram of average spectrum similarity under a distributed strain from 1000 to 3000 µε with different fiber gauge lengths using the proposed method based on the local spectrum (C) and conventional method based on the whole spectrum (P).](image)

Figure 6. Average spectrum similarity under a distributed strain from 1000 to 3000 µε with different fiber gauge lengths using the proposed method based on the local spectrum (C) and conventional method based on the whole spectrum (P).

Experiments under different spatial resolutions (3mm, 5mm, 1cm and 2cm) for measuring a large distributed strain are conducted. Distributed strains ranging from 1000 to 3000 µε at a step of 400 µε are loaded on the segment between 1.3 m to 1.6 m along SMF. The proposed method is used to process sensing signals and achieve distributed strains. As loaded strain increasing, the spectrum shift
increases linearly. According to Figure 10, this property is stable even 3000 µε strain is loaded. With the improvement of the spatial resolution, the smoothness of the spectrum shifts lines in the strain zone became worse than those under low spatial resolution. There might be some difference between the location of the start point of the strain zone under different spatial resolutions. It is mainly caused by different spatial resolutions. Window length in STFT is determined by the spatial resolution, and it influences the start point location. Some points might be unrecognized in the large window length. It is also observable when large strain (over 1000µε) is loaded strain discrimination keeps stable and accurate even the fiber gauge length is downwards to 3 mm. Therefore, the influences caused by fake peaks and multi-peaks are controlled by the proposed OFDR method. A large measurable range OFDR method under a high spatial resolution is achieved.

\[ \Delta \lambda = k \varepsilon \]  

where, \( \Delta \lambda \) is the spectrum shift, \( k \) is the sensitivity coefficient and \( \varepsilon \) is the strain.

According to Fig. 7, calibration is performed as follows. The strain coefficient of a particular fiber under different spatial resolutions may be calibrated in a straightforward manner by fitting the spectrum shift and a corresponding applied strain distributed linearly. The spectrum shift of the RS spectrum has a linear relationship with strain:

Figure 7. Large distributed strain sensing results with different spatial resolutions.

(a) 2 cm spatial resolution  
(b) 1 cm spatial resolution  
(c) 5 mm spatial resolution  
(d) 3 mm spatial resolution

The ratio of spectrum shift under different spatial resolutions (2cm, 1cm, 5mm and 3mm) to applied strain is 0.1586 GHz/µε, 0.1587GHz/µε, 0.1586GHz/µε and 0.1587GHz/µε, respectively. And the nonlinearity is less than 0.5%. The function of a given fiber is quite agreed with different spatial resolutions are selected.
Figure 8. Experiments on the sensing sensitivity of the distributed strain under different spatial resolutions.

Next experimental target of small strain sensing were done. Distributed strains from 10 to 100 µε at a step of 10 µε are loaded between 0.8 m to 0.9 m along SMF. As the Figure 9 shows, the noise floor in the measurements is low and stable. With different strain loads, the maximum values of the noise floor are below 0.8 GHz, the minimum values of the noise floor are over -1 GHz and the standard deviations of it below 0.3 GHz. Thus, this noise could influence small strain sensing hardly. As you can see, the performance of proposed method under small strain load is stable and accurate.

Figure 9. Experiments on sensing micro distributed strain or strain resolution under the highest spatial resolution of 3 mm.

4. Conclusions
In this paper, a signal processing algorithm proposed for OFDR distributed sensing system with the capability of measuring large distributed strain with a spatial resolution of mm-level has been demonstrated. The spectrum shift of the Rayleigh backscatter which is the function of strain is measured using an improved optical frequency-domain reflectometer (OFDR). This method is improved by matching local ReS on MeS rather than a direct cross-correlation between whole ReS and MeS in conventional OFDR methods. By this method, of similarity is enhanced by 4 times in comparison to conventional OFDR methods when the measured distributed strain ranging from 0 to 3000 µε with a 3 mm long fiber gauge.

Acknowledgments
This work was funded by the National Natural Science Foundation of China (61627816, 51575140), Science Fund for Distinguished Young Scholars of Harbin (RC2016JQ006007), the Key Research and Development Program of Jiangsu Province (BE2018047), Natural Science Foundation of Jiangsu Province (BK20180328) and the Fundamental Research Funds of the Central Universities (021314380095, 021314380136, 021314380116).

References
[1] Barrias, A; Casas, J.R; Villalba, S. A Review of Distributed Optical Fiber Sensors for Civil Engineering Applications. Sensors, 16(5), 748 (2016).
[2] Lamberti, A; Chiesura, G; Luyckx, G; Degrieck, J; Kaufmann, M; Vanlanduit, S. Dynamic Strain Measurements on Automotive and Aeronautic Composite Components by Means of Embedded Fiber Bragg Grating Sensors. Sensors, 15(10), 27174-27200 (2015).

[3] Jothibusu, S; Du, Y; Anandan, S; et al. Strain monitoring using distributed fiber optic sensors embedded in carbon fiber composites. Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems, 10598, 105980I (2018).

[4] Zhou, D.P; Wenhai L; Liang C; Bao, X.Y. Distributed Temperature and Strain Discrimination with Stimulated Brillouin Scattering and Rayleigh Backscatter in an Optical Fiber. Sensors, 13(2), 1836-1845 (2013).

[5] Ding, Z; Yang, D; Du, Y; Zhou, Y; Xu, Z; Liu, K; Jiang, J; Liu, T. Note: Improving Distributed Strain Sensing Sensitivity in OFDR by Reduced-Cladding Single Mode Fiber. Review of Scientific Instruments, 87(12), 126106 (2016).

[6] Song, J; Li, W; Lu, P; et al. Long-Range High Spatial Resolution Distributed Temperature and Strain Sensing Based on Optical Frequency-Domain Reflectometry. IEEE Photonics Journal, 6(3):1-8 (2014).

[7] Kreger, S.T; Gifford, D.K; Froggatt, M.E; Alex K. Sang, A.K; Duncan, R.G; Wolfe, M.S; Soller, B.J. High-Resolution Extended Distance Distributed Fiber-Optic Sensing Using Rayleigh Backscatter. SPIE Smart Structures and Materials and Nondestructive Evaluation and Health Monitoring, 6530, 10 (2007).

[8] Ahlgren, P; Bo, J; Rousseau, R. Requirements for a cocitation similarity measure, with special reference to pearson's correlation coefficient. Journal of the Association for Information Science & Technology 2010, 54(6), 550-560.

[9] Kiers, H. A. L. Weighted least squares fitting using ordinary least squares algorithms. Psychometrika, 62(2), 251-266 (1997).

[10] Miller, S.J. The Method of Least Squares. in Brown University (2006).

[11] Froggatt, M.E, Moore, J.P. Apparatus and method for measuring strain in optical fibers using Rayleigh scatter., U.S. Patent 6,545,760 (2003).

[12] Ahn, T. J; Lee, J. Y; Kim, D. Y. Suppression of nonlinear frequency sweep in an optical frequency-domain reflectometer by use of hilbert transformation. Applied Optics, 44(35), 7630-4 (2005).