Dual-Path Phase-Sensitive OTDR for Simultaneously Individual Vibration Monitoring

Kun Zhu[1], Xian Zhou[2], Chao Shang[3], Wenghong Chung[3], Hua-Yaw Tam[3], and Chao Lu[1]
[1]*Photonics Research Centre, Department of Electronic and Information Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR, PR China*
[2]*Research Center for Convergence Networks and Ubiquitous Services, University of Science & Technology Beijing, No.30 Xue Yuan Road, Haidian, Beijing, 100083, China*
[3]*Photonics Research Centre, Department of Electrical Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong SAR, PR China*
kun.zhu@polyu.edu.hk

Abstract: We present and experimentally demonstrate a dual-path phase-sensitive OTDR system based on frequency division multiplexing technology. Vibrations along both 2.5 km and 8.5 km branches can be detected simultaneously with individual monitoring requirement.
OCIS codes: (060.2370) Fiber optics sensors; (120.0120) Remote sensing and sensors; (120.5820) Scattering measurements; (290.5870) Scattering, Rayleigh.

1. Introduction

Optical time-domain reflectometry (OTDR) technology has been deeply investigated since 1980s, and nowadays it has been developed maturely as a commercial instrument to characterize and troubleshoot optical fiber in telecommunication networks [1]. Unlike traditional OTDR, phase-sensitive OTDR utilizes coherent laser sources with narrow linewidth, thus can be used for dynamic vibration measurement and monitoring along optical fiber with coherent Rayleigh backscattering detection and analysis [2,3]. To improve the performance of the phase-sensitive OTDR, different schemes based on various structures and signal processing methods have been proposed and investigated, such as using Raman and Brillouin amplification to increase the sensing length [4], using optical pulse compression technology with linear frequency modulation (LFM) to improve the spatial resolution of the vibration location [5], using frequency division multiplexing (FDM) to enlarge the measured frequency range of the detected vibration signal [6,7], etc.

In this paper, we present a dual-path phase-sensitive OTDR system based on frequency division multiplexing (FDM) technology. In the proposed distributed fiber sensing system, two individual fiber branches can be monitored simultaneously, and the possible vibrations along both the branches can be detected. The parameters for monitoring both the branches, such as optical pulse width, repetition rate and launch power, can be set individually. In the experimental demonstration, the sensing distance of the two branches is set to be 8.5 km and 2.5 km respectively. With FDM and heterodyne detection technique, the Rayleigh backscattering signals from both the branches can detected and demodulated. The locations of vibration along the two fiber branches are both detected, which shows that our scheme can be extended and used in distributed vibration sensing system with multiple paths.

2. Principle and experimental setup

Fig. 1 shows the experimental setup of the proposed dual-path phase-sensitive OTDR system. A narrow-linewidth laser is used as the coherent optical source. The output lightwave is split by two optical couplers into three parts, which are used for the upper branch, the lower branch and as the LO light respectively. In the upper branch, the light is first modulated by an acousto-optic modulator (AOM) with a frequency shift of 100 MHz. The pulse width is 200ns and the repetition rate is 10 kHz. The optical pulse is amplified by an erbium-doped fiber amplifier (EDFA) and filtered by a 100 GHz optical bandpass filter before it is launched into a span of 8.5 km fiber. Along the fiber, a length of 10 m bare fiber is coiled around a cylindrical piezoelectric transducer (PZT) at the distance of 7.5 km. The backscattering signal from the 8.5 km fiber is then amplified by another EDFA and filtered by the followed optical bandpass filter before being received. For the lower branch, the link setup is the same except for the parameter settings. In the lower branch, the frequency shift of the AOM is 80 MHz. The optical pulse is with a width of 100 ns and a repetition rate of 40 kHz. The fiber under test is with a distance of 2.5 km. The PZT is coiled around by a 1 m bare fiber at the position of 2 km. In the receiver end, the backscattering signals from both upper and lower branches are coupled first, and then coupled with the LO together. The beating signal is received by a balanced photodetector (BPD).

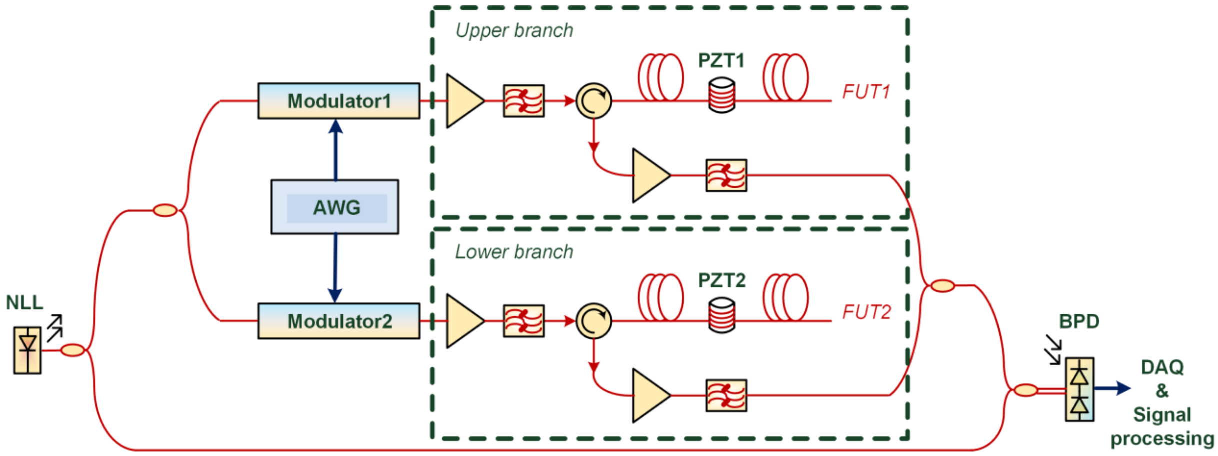

Fig. 1 Experimental setup of the dual-path phase-sensitive OTDR system.

The received electrical signal is sampled by an oscilloscope with a sample rate of 1 Gs/s. All the signal processing work is done offline. Since the backscattering signals from the two branches are with different frequency shift, i.e. 100 MHz and 80 MHz, respectively, frequency division demultiplexing technology can be used for demodulation. For each branch, a digital bandpass filter centered at certain frequency is used for frequency selection, and then mixed by sinusoidal and cosine signals respectively, at last a digital lowpass filter is followed. Based on these operations, the backscattering signal from each branch can be demodulated individually. Through modal and arctan operations, both the amplitude and phase information of the two branches are retrieved for vibration detection and monitoring.

3. Results and discussion

In the first experiment, separate measurement is made for comparison. In the test for each branch, the EDFAs in the other branch are turned off. Fig. 2 shows the locations of vibrations from both the upper and lower branches. It is obvious that the location of vibration for the upper branch is at around 7475 m, and that for lower branch is at around 1995 m. Since the pulse width for the upper branch is 200 ns, a spatial resolution of 20 m is achieved, which can be seen from the zoomed-in view of Fig. 2 (b). Similarly, for the lower branch, the spatial resolution is 10 m, which can be seen from Fig. 2 (d).

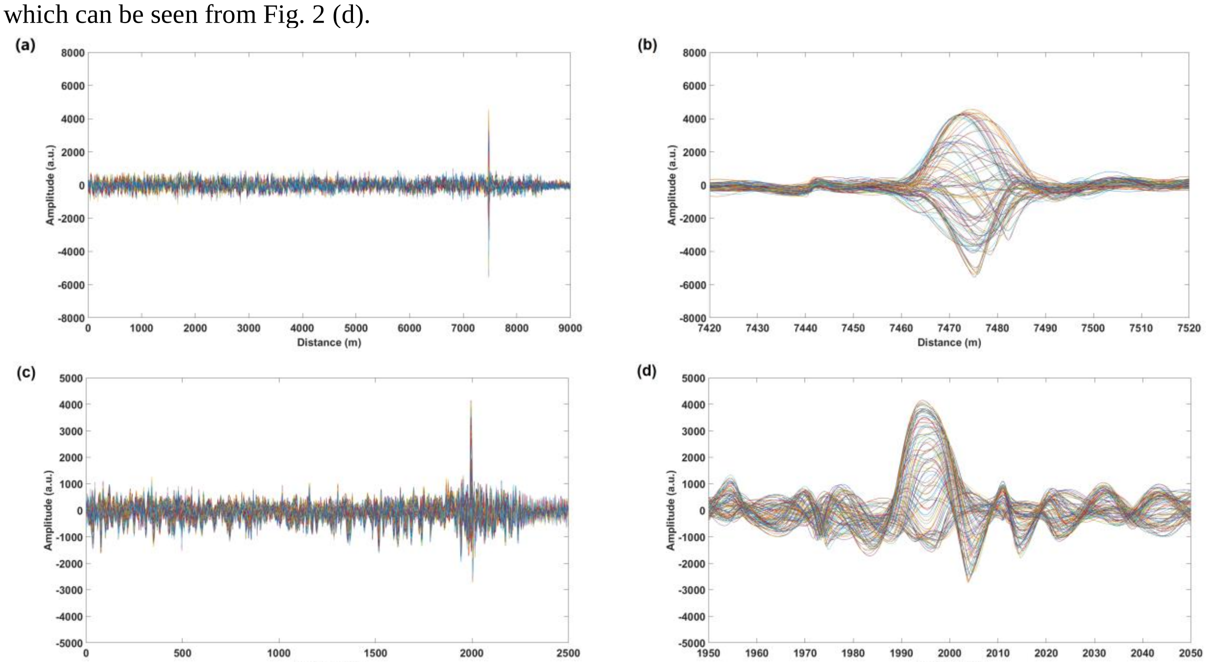

Fig. 2 The detected locations of the individual vibration from both upper and lower branches with separate measurement, (a) for the upper branch with (b) the zoomed-in view of the vibration section, and (c) for the lower branch with (d) the zoomed-in view of the vibration section.

In the following experiment, all the EDFAs are turned on for simultaneously monitoring of the two branches. Demodulation and demultiplexing operations are done as discussed above. Fig. 3 shows the locations of the detected vibrations for the both branches. It can be seen that vibrations at the same locations are detected as shown in Fig. 2 and Fig. 3. The signal-to-noise ratios shown in Fig. 3 are worse, which is caused by the residual frequency parts in the demultiplexing procedure.

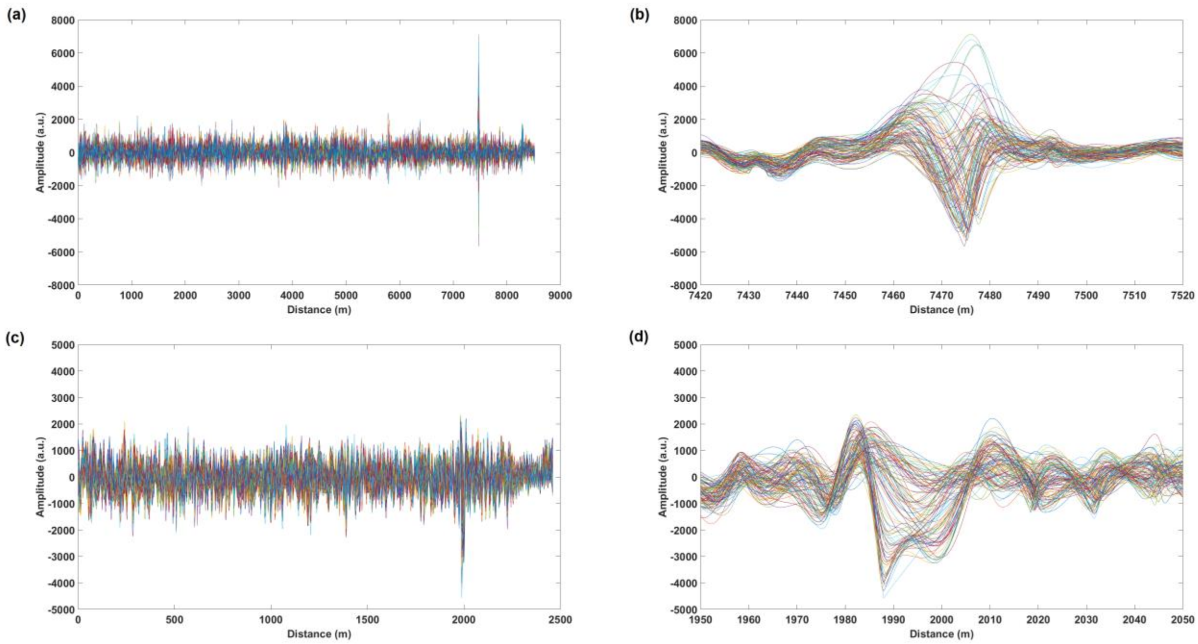

Fig. 3 The detected locations of the individual vibration from both upper and lower branches with simultaneous demodulation based on FDM technology, (a) for the upper branch with (b) the zoomed-in view of the vibration section, and (c) for the lower branch with (d) the zoomed-in view of the vibration section.

4. Conclusion

We have implemented and experimentally demonstrated a dual-path phase-sensitive OTDR system, which is based on frequency division multiplexing and heterodyne detection techniques. With our proposed distributed vibration sensing system, simultaneous monitoring for more than one paths can be realized using only one set of optical source and receiver. The parameters for each sensing path can be adjusted individually, which provides good flexibility for the practical vibration monitoring applications.

5. Acknowledgement

This work is supported by the National Natural Science Foundation of China (NSFC: U1701661); the Research Grants Council (RGC) of Hong Kong, General Research Fund (GRF: PolyU 152658/16E, 152168/17E); The Hong Kong Polytechnic University (H-ZG7E, 1-YW0S, 1-YW3G, 1-ZVFL).

6. References

[1] M. K. Barnoski, S. M. Jensen, "Fiber waveguides: a novel technique for investigating attenuation characteristics," Applied Optics **15**, 2112-2115 (1976).
[2] H. F. Taylor and C. E. Lee, "Apparatus and method for fiber optic intrusion sensing," U.S. patent 5,194,847 (March 16, 1993).
[3] Y. Lu, T. Zhu, L. Chen, X. Bao, "Distributed vibration sensor based on coherent detection of phase-OTDR," Journal of lightwave Technology **28**, 3243-3249 (2010).
[4] Z. N. Wang, J. J. Zeng, J. Li, M. Q. Fan, H. Wu, F. Peng, L. Zhang, Y. Zhou, and Y. J. Rao, "Ultra-long phase-sensitive OTDR with hybrid distributed amplification," Optics letters **39**, 5866-5869 (2014).
[5] B. Lu, Z. Pan, Z. Wang, H. Zheng, Q. Ye, R. Qu, and H. Cai, "High spatial resolution phase-sensitive optical time domain reflectometer with a frequency-swept pulse," Opt. Lett. **42**, 391-394 (2017).
[6] G. Yang, X. Fan, Q. Liu, and Z. He, "Frequency response enhancement of direct-detection phase-sensitive OTDR by using frequency division multiplexing," J. Lightw. Technol. **36**, 1197-1203 (2018).
[7] Z. Wang, Z. Pan, Z. Fang, Q. Ye, B. Lu, H. Cai, and R. Qu, "Ultra-broadband phase-sensitive optical time-domain reflectometry with a temporally sequenced multi-frequency source," Opt. Lett. **40**, 5192-5195 (2015).