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The cornerstone of fiber-optic distributed vibration/acoustic sensing: Φ-OTDR

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Fiber-optic distributed vibration/acoustic sensing (DVS/DAS) technology achieves breakthrough performance and explores broad cornerstone industrial applications.

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Background

Since the phase-sensitive optical time-domain reflectometry (Φ-OTDR) concept was proposed in 1993[1], Φ-OTDR has undergone rapid development and extensive studies. The first practical DVS system based on Φ-OTDR was demonstrated with a powerful narrow linewidth laser in 2008[2]. Φ-OTDR is capable of covering long measurement range while maintaining high sensitivity and spatial resolution along the sensing fiber[3,4]. Based on this, researchers have made great effort on Φ-OTDR sensing performance improvement, including sensing distance, sensitivity, spatial resolution, frequency response range, event recognition accuracy, etc. Based on its superior long-distance and high-resolution distributed vibration/acoustic sensing capabilities, Φ-OTDR technology has been widely used in earthquake monitoring, oil and gas resource exploration, pipeline leak detection, perimeter intrusion monitoring, cable partial discharge detection and other fields with a large number of successful application demonstrations.

In the recent work[5] entitled "Advances in phase-sensitive optical time-domain reflectometry" published in *Opto-Electronic Advances*, DOI: 10.29026/oea.2022.200078, Prof. Liyang Shao et al. present in detail the research progress and applications of DVS/DAS technology based Φ-OTDR. This article was selected as the back cover paper of Volume 3, Issue 5 of OEA in 2022, and was recently selected as a highly cited paper by Web of Science.

Principle

The article first analyzes the sensing principles of DVS-Φ-OTDR based on Raleigh backscattering intensity demodulation and DAS-Φ-OTDR based on phase demodulation. The article focuses on comparing and discussing DAS phase demodulation technologies, including IQ demodulation based on heterodyne detection, Hilbert transform scheme based on heterodyne detection, direct detection method based on 3×3 coupler, and direct detection method based on phase-generated carrier technology. Recently, S. Liu et al. proposed a fast generation method of phase orthogonal signals in the digital domain. By using the phase difference of beat signals between adjacent spatial sampling channels, the fast demodulation of vibration is realized, which greatly reduces the computational complexity of the Φ-OTDR phase demodulation process[6].

Performances

Φ-OTDR enables distributed measurements of vibration,

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dynamic strain, etc., which can usually be evaluated by several technical parameters, mainly including sensing distance, signal-to-noise ratio, sensitivity, frequency response range, spatial resolution, and event recognition capability. This review article provides a detailed and valuable summary and analysis of the recent progress in improving key parameters of Φ-OTDR in recent years.

Φ-OTDR uses the very weak backscattered light in fiber as the signal. With the increase in the sensing distance, the signal decays exponentially, which renders long-distance measurement difficult. In 2014, F. Peng et al. proposed to apply heterodyne detection and first-order bidirectional Raman amplification to Φ-OTDR, increasing the sensing distance to 131.5 km[7]. In the same year, Z. Wang et al. proposed a hybrid distributed amplification method combining first-order Raman amplification, second-order Raman amplification, and Brillouin amplification to achieve a sensing distance of 175 km[8].

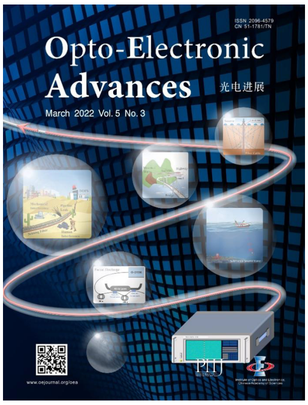

Fig. 1 | Back cover of Volume 3, Issue 5 of OEA in 2022.

SNR is the key parameter that determines the performance of Φ-OTDR. It not only determines the sensing distance, but also the sensitivity and accuracy. On the one hand, SNR can be improved by increasing the signal strength by amplifying the optical power of the probe and compensating the fiber transmission loss, and suppressing the system noise. Some methods have also been proposed to suppress low-frequency noise[9–13]. Data with high SNR are usually large, which causes many problems in practice. In 2022, F. Yu et al. explored the effect of sampling accuracy on phase demodulation of a Φ-OTDR system. The researchers successfully recovered the sinusoidal disturbance signal imposed by the PZT from the original data with 1bit precision, and the SNR reached 58.03 dB, which is only 5 dB lower than the 16bits data[14]. Researchers combined the ultra-low sampling accuracy technology with the down-sampling technology to show a new data storage scheme (that is, storing the original data with low sampling rate and low accuracy), which can not only greatly reduce the amount

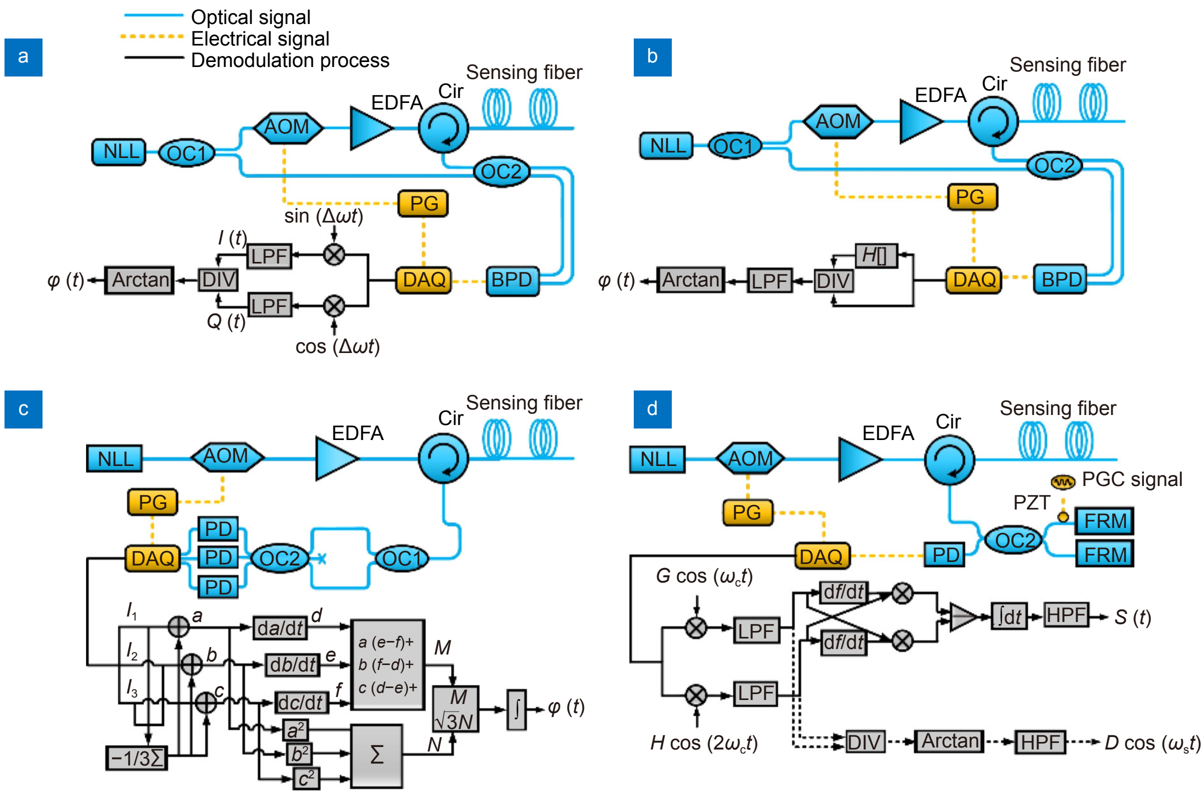

Fig. 2 | Setup of DAS-Φ-OTDR system with different demodulation methods[5].

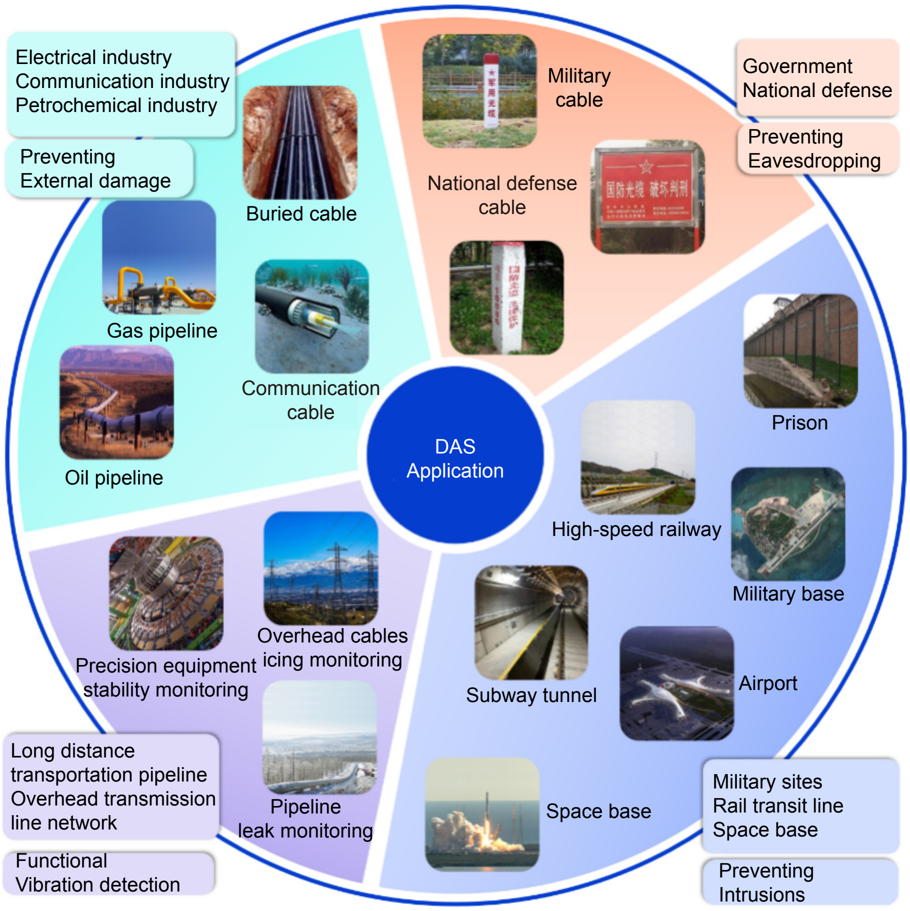

Fig. 3 | Application of DAS-Φ-OTDR system[17,18].

of system data, but also provide more space for feature selection in the later work of disturbance identification[15].

The spatial resolution of Φ-OTDR refers to the shortest distance between distinguishable events. It reflects the spatial recognition and positioning capabilities and is related to probe pulse width, photodetector sampling rate, acquisition card, and so on.

In order to solve the problem that Φ-OTDR systems can locate external interference but cannot distinguish different types of intrusion events, pattern recognition algorithms for Φ-OTDR signal post-processing have been widely studied in recent years[4]. Pattern recognition algorithms like YOLO[16] can automatically classify detected vibration signals into interested intrusions and unwanted environmental noise based on the signal characteristics of the vibration signal, greatly improving the alarm accuracy and reducing the false alarm rate of the system.

Applications

Through appropriate optical configurations, Φ-OTDR can measure vibration, dynamic strain or temperature distribution over long distances with high spatial resolution. This capability makes Φ-OTDR widely applicable in different scenarios. This review summarizes the recent developments of Φ-OTDR in various application fields, including geological exploration, perimeter monitoring, traffic sensing, partial flow monitoring, and other applications[17,18].

An ultra-sensitive distributed fiber-optic sensing seismometer called uDAS, independently developed by Optical Science and Technology (Chengdu) Ltd. of China National Petroleum Corporation (CNPC), based on coherent detection and multi-frequency modulation method proposed by the Chinese researchers[19,20], has been applied in all oil/gas fields of CNPC. Through the combination of optical cables in oil well and surface geophones, higher resolution seismic data were obtained, which effectively improves the accuracy of formation modeling and obtains higher quality data, providing a strong technical guarantee for reservoir characterization and description. The successful development and large-scale application of the uDAS instrument has promoted the extension of geophysical exploration technology from oil/gas exploration to reservoir development, opened a new era of high-precision borehole and ground combined stereoscopic exploration and reservoir development, and also demonstrated the great advantages of the DAS technology.

Some cases apply Φ-OTDR to new application scenarios, such as detecting pest infections, while others introduce special fibers or advanced post-processing algorithms to convert the measurement of target physical parameters into vibration detection, strain or temperature changes along the sensing fiber, such as gas concentration levels and fiber bending directions. These novel applications have demonstrated that Φ-OTDR systems are promising tools applicable to various scenarios with enormous potential.

Future

Future research would focus on exploring new operating principles, developing key devices, improving system performance, and expanding application areas of Φ-OTDR. In terms of operating principles, developing new light sources such as optical frequency combs and special sensing fibers including uwFBG arrays, fs-lasing enhanced fibers, or multicore fibers will further improve the performance of Φ-OTDR. In terms of data interpretation methods, advanced signal processing methods in artificial intelligence and computer science can be adopted. In practical engineering applications, it is necessary to develop practical interpretation algorithms that are based on unsupervised learning. In addition, Φ-OTDR will also be applied to more fields such as determining the event features and locations of underground activities or airborne aircraft and so on.

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