Physics and applications of Raman distributed optical fiber sensing

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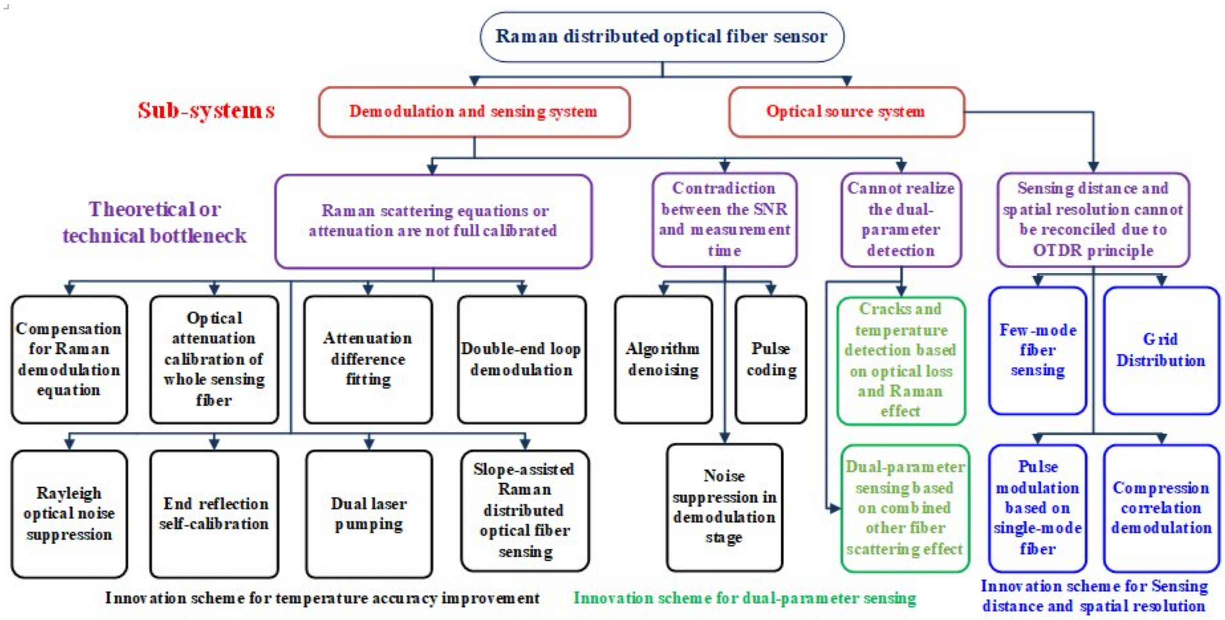

In this chart, the red words represent the sub-systems. The black words represent the optimization scheme of temperature measurement accuracy, the blue words represent the optimization scheme of sensing distance and spatial resolution, the green words represent the dual-parameter sensing demodulation scheme, the purple words represent the theoretical or technical bottleneck of the system. Credit: Jian Li and Mingjiang Zhang

Raman distributed optical fiber sensing has been demonstrated to be a mature and versatile scheme that presents great flexibility and effectivity for the distributed temperature measurement of a wide range of engineering applications. The past decades have witnessed its rapid development and extensive applicability ranging from scientific research to industrial manufacturing.

To satisfy the requirements of different engineering applications, researchers carried out some studies with the main purpose of developing high-performance Raman distributed optical fiber sensing, and explored various new theories and solutions to improve the performance of the system. This chapter introduces and summarizes the performance optimization of the sensing systems considering four aspects: temperature measurement accuracy, sensing distance, spatial resolution, and multi-parameter monitoring. The illustration above presents the demodulation schemes for performance improvement of distributed optical fiber sensing. Its sub-systems mainly consist of the demodulation and sensing system, and the optical source system. The connecting lines represent the theoretical or technical improvement of the scheme based on the above key components.

Temperature measurement accuracy is the key sensing index of the system, which denotes the deviation of the measured temperature from the actual temperature value. It can be determined by the standard deviation or uncertainty of the measured temperature. The main factors that affect the temperature measurement accuracy of the system include: (1) the optical attenuation difference between the Raman Stokes anti-Stokes signals, (2) the limitation of SNR, (3) the demodulation deviation of the Raman transmission equation, and (4) the principle of optical time domain reflection causing the temperature signal in the spatial scale of the pulse width to be compressed into a point. The temperature signal detected at this point is less than the actual temperature. In this case, researchers proposed and demonstrated a variety of advanced temperature demodulation programs to improve the temperature accuracy.

Spatial resolution and sensing distance are also the key indicators of the effective sensitivity of Raman distributed optical fiber sensing systems. The spatial resolution is defined as the minimum distance that the optical fiber sensing system can distinguish between two adjacent points. A bottleneck lies in balancing the sensing distance with the spatial resolution. Reducing the pulse width can optimize the system's spatial resolution, but it deteriorates the system's sensing distance. To optimize the sensing distance and spatial resolution performance of the system, researchers have proposed many advanced solutions.

At present, in the field of modern industrial monitoring, there is a strong demand for dual-parameter or even multi-parameter collaborative detection. Unfortunately, traditional Raman distributed optical fiber sensing is a single-parameter detection technology based on Raman scattering, which is unable to meet these requirements. In this case, development of a dual-parameter detection scheme based on a single optical fiber becomes an important technical problem for Raman distributed optical fiber sensing. For the purpose of solving the above-mentioned problems, researchers have proposed a variety of advanced solutions.

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