Surpassing 1,000,000 resolving points in chaotic Brillouin sensing

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Optical fiber sensors have played a pivotal role in structural health monitoring for over half a century, owing to their inherent advantages such as lightweight design, compactness, immunity to electromagnetic interference, and their ability to enable distributed sensing.[1] Within this diverse range of sensors, Brillouin scattering has emerged as a widely adopted principle for distributed measurements of strain and temperature.[2] Brillouin-based distributed sensors can be categorized into reflectometry and analysis methods, encompassing time, frequency, and correlation domains. The evaluation of Brillouin sensing systems entails the consideration of various parameters, with the number of effective resolving points N_{eff} being a critical factor representing the ratio of the measurement range to spatial resolution. While significant progress has been made in time-domain methods,[3–5] their limited signal-to-noise ratio (SNR) and nonlocal system response confine their measurement ranges to a few kilometers. In contrast, correlation-domain methods employing continuous waves offer promising prospects for achieving long-range measurements spanning tens of kilometers, thus circumventing the limitations imposed by pulse width.[6–8] Among these techniques, Brillouin optical correlation-domain analysis (BOCDA) stands out as a particularly compelling approach, offering enhanced performance and a higher SNR.[8]

In the pursuit of increasing N_{eff}, the fiber-optic sensing community has witnessed intense competition.[9–11] Techniques such as standard BOCDA based on sinusoidal frequency modulation have achieved N_{eff} values close to 1 million through differential measurement[9] and time-domain data processing.[10] By combining phase coding and pump pulse modulation, N_{eff} exceeding 2 million has been attained.[11] However, further enhancing the measurement range while maintaining spatial resolution remains a challenge, and these approaches often lack cost efficiency due to the reliance on high-bandwidth modulators. Consequently, an urgent demand arises for a novel BOCDA configuration that decouples spatial resolution from modulation or coding parameters, thereby ensuring both superior performance and cost effectiveness.

In a groundbreaking study published in *Advanced Photonics Nexus*,[12] Mingjiang Zhang and his team from Taiyuan University of Technology propose a remarkable solution: the long-range chaotic BOCDA system. This innovative approach utilizes an optimized time-gated scheme and a differential denoising configuration. The optimized time-gated scheme, with its improved extinction ratio, effectively eliminates the adverse impact of time delay signature, resulting in more accurate and reliable measurements. Meanwhile, the differential denoising scheme plays a vital role in enhancing the signal-to-background ratio of the chaotic Brillouin gain spectra, effectively suppressing accumulated nonzero noise along the fiber under test (FUT). These techniques achieve a significant increase in N_{eff}, surpassing the 1 million mark, without necessitating high-bandwidth modulators or incurring additional system costs. Furthermore, this distributed strain sensing system demonstrates exceptional robustness and accuracy.

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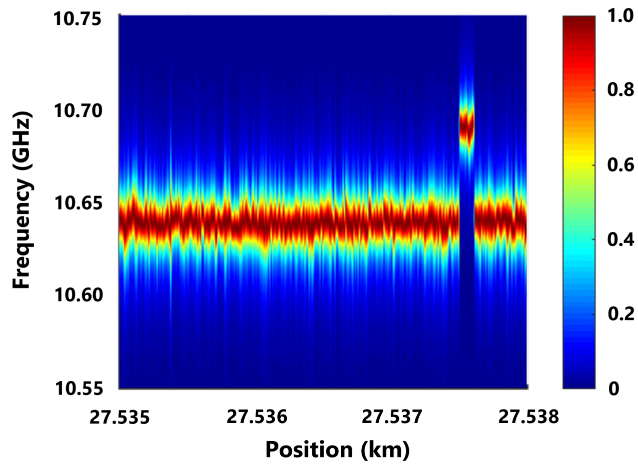

Fig. 1 Distribution of Brillouin gain spectra measured by the long-range chaotic BOCDA system. The figure demonstrates the successful detection of a 10-cm-long strained section located near the distal end of a 27.54-km-long sensing fiber. Remarkably, the system achieves an exceptional spatial resolution of 2.69 cm, resulting in an impressive number of effective resolving points reaching 1,020,000. Figure adapted from Ref. 12.

A distinguishing aspect of the long-range chaotic BOCDA system resides in its reliance on laser bandwidth rather than modulation parameters to determine spatial resolution.[13,14] This characteristic offers profound advantages by enabling an extended measurement range without compromising the exceptional spatial resolution. An experimental result presented in Fig. 1 unequivocally demonstrates the correct detection of a 10-cm-long strained section near the distal end of a 27.54-km-long FUT, with a confirmed spatial resolution of 2.69 cm and an N_{eff} value of 1,020,000.

The long-range chaotic BOCDA technique holds immense promise across various fields, including structural health monitoring, disaster warning systems, intelligent applications within the Internet of Things, and industrial sectors such as oil and gas pipelines, power grids, transportation systems, and environmental monitoring. However, the practical application of this technique presents a future challenge in terms of the substantial measurement time required for distributed sensing along the entire length of the FUT. Nevertheless, a compelling avenue emerges through the distinctive attribute of random accessibility intrinsic to BOCDA, enabling strategic selection of specific sensing points along the FUT. By leveraging this unique feature, it becomes possible, for instance, to initiate distributed sensing along the entire FUT with a comparatively lower spatial resolution, followed by subsequent precise distributed sensing in irregular sections. This optimization strategy harmoniously balances measurement time and spatial resolution, facilitating the effective deployment of the technique.

In summary, the long-range chaotic BOCDA system represents a groundbreaking achievement in the fiercely competitive field of fiber-optic sensing. By employing an optimized time-gated scheme and a differential denoising configuration, this innovative approach has pushed the boundaries of long-range distributed strain sensing, delivering an N_{eff} value exceeding 1 million. What sets this technique apart from other high N_{eff} methods is its unique characteristic: the spatial resolution is determined by the laser bandwidth rather than modulation or coding parameters. Consequently, the spatial resolution remains uncompromised even as the measurement range is further extended—a remarkable advantage. In addition, the absence of high-bandwidth modulators in the system ensures cost efficiency, making it an appealing solution for real-world implementation. With its outstanding performance and ingenuity, the long-range chaotic BOCDA system has expanded the horizons of fiber-optic sensing and is poised to drive future developments in the field. The scientific community eagerly anticipates the profound impact and advancements that will stem from this remarkable contribution.

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Yosuke Mizuno is a distinguished researcher in the field of distributed fiber sensing and polymer optics. He received his BE, ME, and DrEng degrees in electronic engineering from the University of Tokyo, Japan, in 2005, 2007, and 2010, respectively. From 2010 to 2020, he held the positions of Research Fellow and Assistant Professor at Tokyo Institute of Technology. Since 2020, he has been serving as an Associate Professor at the Faculty of Engineering, Yokohama National University, Japan. His pioneering work in 2008 led to the development of the Brillouin optical correlation-domain reflectometry (BOCDR) technique, revolutionizing distributed fiber sensing. His research has encompassed various significant contributions, including the observation of Brillouin scattering in polymer optical fibers in 2010, the discovery of the polymer fiber fuse phenomenon in 2014, the development of ultrahigh-speed BOCDR in 2016, and the realization of polymer fiber-based magnetic field sensing in 2021. He has also made significant progress in correlation-domain LiDAR technology in the same year. His exceptional contributions to the field have been widely recognized and honored with numerous prestigious awards. In 2021, he was bestowed with the Young Scientist's Award, Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology (MEXT) in Japan. This recognition signifies his exemplary achievements as a young researcher in the country and highlights the impact of his work.