

NEWS & VIEWS

Open Access

# Optimizing multi-parameter distributed fiber sensors: a hybrid Rayleigh-Brillouin-Raman System approach

Kwang Yong Song<sup>1</sup>✉

## Abstract

An optimized single-end hybrid Rayleigh, Brillouin, and Raman distributed fiber sensing system has been developed for simultaneous measurement of multiple parameters. This system integrates 3-bit pulse coding for the Raman signal and the Brillouin amplification of the Rayleigh-backscattered signal, discriminating strain, temperature, and vibration using a single sensing fiber.

A distributed optical fiber sensor (DOFS) is an intrinsic sensor that is able to determine the spatial distribution of one or more measured parameters (or measurands) at each and every point along a sensing fiber. Today, DOFS has gained widespread usage, primarily for real-time monitoring of the structural integrity of expansive civil infrastructures and surveying environmental conditions<sup>1</sup>. These sensors serve as fundamental components in smart sensing systems, playing a crucial role in the development of smart cities and the implementation of smart factories equipped with automated manufacturing processes.

DOFS are capable of measuring various physical quantities such as strain<sup>2</sup>, temperature<sup>3,4</sup>, pressure<sup>5</sup>, vibration<sup>6</sup>, acoustic impedance<sup>7</sup>, and more. These sensors operate utilizing elastic or inelastic light scatterings within optical fibers, which are Rayleigh backscattering (RBS), Brillouin scattering (BS), and Raman scattering (RS). In most applications, strain, temperature, and vibration are the primary variables of interest, and each type of scattering exhibits distinct sensitivity to these measurands. For example, RS, involving scattering by optical phonons, exclusively responds to temperature change making it ideal for implementing distributed temperature sensor (DTS), and BS, relying on scattering by acoustic phonons,

are sensitive to both strain and temperature. Meanwhile, RBS, arising from the random fluctuation of refractive index, is particularly suitable for measuring vibration, enabling the realization of distributed acoustic or vibration sensor (DAS / DVS).

The utilization of multiple scatterings presents a direct approach to building DOFS capable of simultaneously measuring multiple measurands. This has prompted researchers to propose diverse hybrid systems<sup>8,9</sup>. One such example involves combining RBS and BS as the foundation for a hybrid system aiming to detect vibration concurrently with strain or temperature. In these systems, Brillouin optical time domain analysis (BOTDA) or reflectometry (BOTDR) is employed to measure strain or temperature, while phase-sensitive optical time domain reflectometry (phase-OTDR or  $\phi$ -OTDR) is utilized for vibration measurement<sup>8</sup>. However, a significant challenge hindering the practical application of this hybrid system is the cross-sensitivity of strain and temperature observed in both RBS and BS signals. While integrating an RS-based DTS system into the hybrid setup could potentially offer a solution for discriminating between strain and temperature variations, it significantly amplifies the complexity of the system.

In the work newly published in *Light: Advanced Manufacturing*<sup>10</sup>, the research team led by Xinyu Fan and Zuyuan He at Shanghai Jiao Tong University proposed a new approach for optimizing hybrid DFOS systems. This

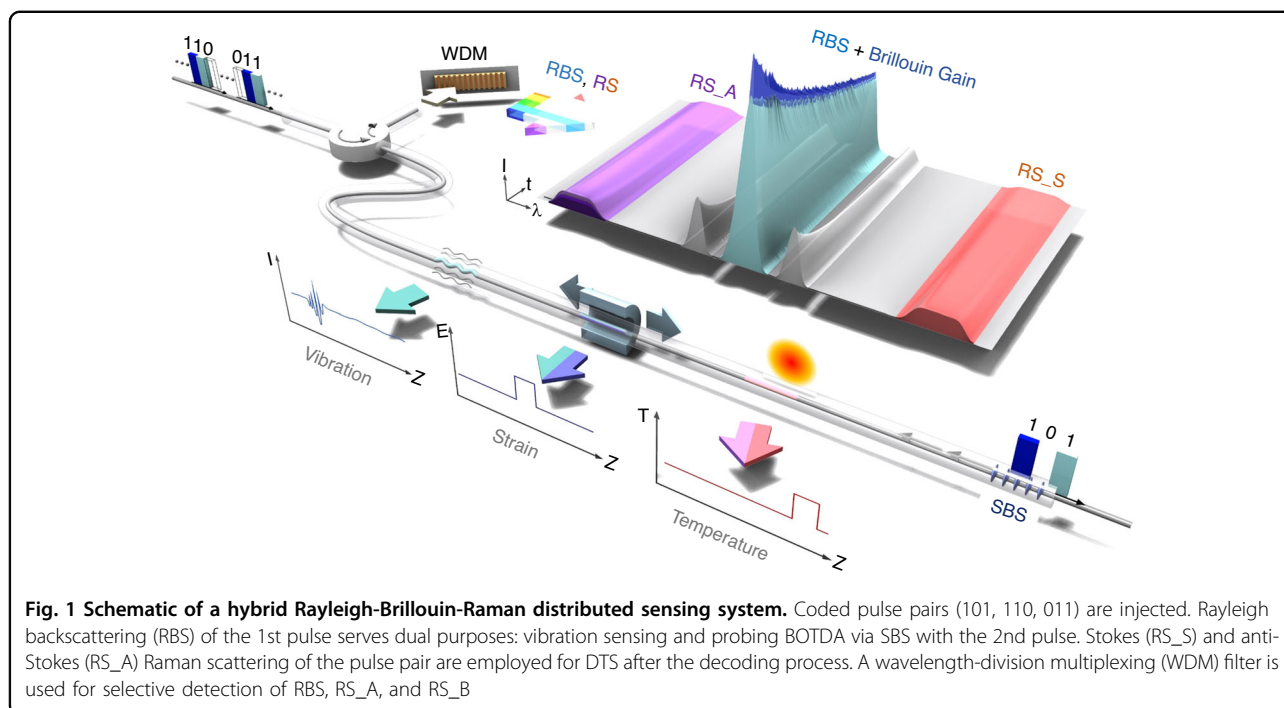
Correspondence: Kwang Yong Song (songky@cau.ac.kr)

<sup>1</sup>Dept. of Physics, Chung-Ang University, 84 Heukseok-ro, Dongjak-gu, Seoul 06974, Korea

© The Author(s) 2024



**Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.



method leverages the combined use of RBS, BS, and RS signals while employing a single-end measurement configuration. In the proposed system two optical pulses with slightly different optical frequencies are injected into a sensing fiber, where the RBS signal from the initial pulse is amplified by the subsequent pulse through Brillouin amplification by stimulated BS (SBS; Fig. 1).

In general, BOTDA utilizing the SBS between counter-propagating light waves offers the advantage of generating larger signal amplitudes compared to BOTDR which involves spontaneous BS. However, BOTDA necessitates access to both ends of the sensing fiber, limiting its practicality in various applications. The method utilizing RBS as the probe for BOTDA was recently developed by the team of Fan and He<sup>11</sup>, and has also been applied for this work. This approach effectively merges the RBS and BS measurements, ensuring a substantial signal amplitude through SBS while maintaining a single-end access configuration to the sensing fiber. Furthermore, this method simplifies signal processing in contrast to earlier hybrid RBS and BS systems<sup>8,9</sup>, as it solely employs the RBS light wave for demodulating the probe for both BS and RBS.

For the implementation of DTS a 3-bit simplex coding method is employed for encoding the two successive optical pulses. Given the optical frequency offset between the two pulses for SBS ( $\sim 10$  GHz) is negligible compared to the spectral width of RS signal (several THz), two optical pulses can be assumed to have an identical frequency for generating RS. While various pulse coding methods have been utilized to improve the signal-to-noise ratio (SNR) in

long-range DOFS systems<sup>3,12</sup>, it is noteworthy that the pulse coding strategy employed in the proposed hybrid system not only enhances the SNR, but also maintains the spatial resolution of DTS to the level of single pulse width when operating with two successive pulses for RBS-BS scheme.

The measurement accuracies demonstrated by the developed hybrid system are as follows:  $10 \text{ p}\epsilon/\sqrt{\text{Hz}}$  for  $\phi$ -OTDR, 0.58 MHz for BOTDA, and  $0.5^\circ\text{C}$  for DTS achieved with a spatial resolution of 10 m within a sensing range of 9 km. These reported accuracies align with those of conventional DOFS systems operating within similar sensing ranges. While certain independent system schemes can achieve superior performances, they often necessitate additional schemes or devices, consequently increasing system complexity and cost. For instance, conventional BOTDA requires two-end access to the sensing fiber. In contrast, the proposed hybrid system achieves multi-parameter sensing while fully isolating each parameter with a single-end access configuration to the sensing fiber.

The peak power of optical pulses used in the proposed system must be maintained lower than that of conventional DTS systems due to limitations imposed by detrimental nonlinear effects on BS, which poses challenges in reducing the spatial resolution. Further enhancement in the sensing range and the spatial resolution without significantly compromising the system's simplicity are anticipated, potentially through the application of advanced scheme like distributed amplification<sup>13</sup>.

In conclusion, the proposed system offers a significant reduction in system complexity and cost compared to

three sets of conventional independent systems. The pivotal elements in effectively merging the RBS, BS, and RS measurements with a single light source involve utilizing RBS as the probe for BS and implementing the pulse coding technique for RS. The developed approach appears particularly suitable for long-distance distributed sensing applications that demand simultaneous measurement of multiple parameters, such as real-time and long-term health monitoring of rail transit systems.

#### Acknowledgements

This research was supported by Program of Strengthening International Cooperation for Quantum Technology through the National Research Foundation of Korea (NRF), funded by the Korean government (Ministry of Science and ICT (MSIT)) (No. NRF-2022M3K4A1097124).

Published online: 05 February 2024

#### References

- Hartog, A. H. *An Introduction to Distributed Optical Fiber Sensors* (CRC Press, 2017).
- Bao, X. Y., Zhou, Z. C. & Wang, Y. Review: distributed time-domain sensors based on Brillouin scattering and FWM enhanced SBS for temperature, strain and acoustic wave detection. *PhotonIX* **2**, 14 (2021).
- Li, J. & Zhang, M. J. Physics and applications of Raman distributed optical fiber sensing. *Light Sci. Appl.* **11**, 128 (2022).
- Wang, C. Y. et al. Chaos Raman distributed optical fiber sensing. *Light Sci. Appl.* **12**, 213 (2023).
- Kim, Y. H. et al. Distributed measurement of hydrostatic pressure based on Brillouin dynamic grating in polarization maintaining fibers. *Opt. Express* **24**, 21399–21406 (2016).
- Lu, Y. L. et al. Distributed vibration sensor based on coherent detection of phase-OTDR. *J. Lightwave Technol.* **28**, 3243–3249 (2010).
- Chow, D. M. et al. Distributed forward Brillouin sensor based on local light phase recovery. *Nat. Commun.* **9**, 2990 (2018).
- Coscetta, A. et al. Hybrid Brillouin/Rayleigh sensor for multiparameter measurements in optical fibers. *Opt. Express* **29**, 24025–24031 (2021).
- Hartog, A. H. & Englisch, F. V. Non-linear interactions with backscattered light: a truly single-ended Brillouin optical time-domain analysis technique. *J. Lightwave Technol.* **37**, 2386–2402 (2019).
- Huang, L. J. et al. Single-end hybrid Rayleigh Brillouin and Raman distributed fibre-optic sensing system. *Light Adv. Manuf.* **4**, 171–180 (2023).
- Huang, L. J. et al. Hybrid distributed fiber-optic sensing system by using Rayleigh backscattering lightwave as probe of stimulated Brillouin scattering. *J. Lightwave Technol.* **41**, 4374–4380 (2023).
- Soto, M. A. et al. Simplex-coded BOTDA fiber sensor with 1 m spatial resolution over a 50 km range. *Opt. Lett.* **35**, 259–261 (2010).
- Sun, X. Z. et al. Ultra-long Brillouin optical time-domain analyzer based on distortion compensating pulse and hybrid lumped–distributed amplification. *APL Photon.* **7**, 126107 (2022).