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Distributed optical fiber sensors: what is known and what is to come

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This perspective article delves into the current performance limitations of distributed optical fiber sensors and proposes avenues for future advancements, as envisioned by the author, whose four-decade-long career has been dedicated to this transformative field. By upscaling the dimension of collected data, distributed sensors are essential in enabling large-scale data acquisition for "big data" systems, and optical fibers offer a unique, highly effective platform for distributed sensing. This article examines the ultimate performance achievable using state-of-the-art technologies across different sensor types. It further explores potential innovations, such as the adoption of advanced signal processing, novel fiber designs, and artificial intelligence, that could drive significant improvements in sensing performance and applications.

KEYWORDS

optical fiber sensor, distributed fiber sensor, distributed temperature sensing, Rayleigh scattering, Brillouin scattering, Raman scattering

1 Introduction

Distributed sensors hold a unique position in the realm of sensing technologies. Unlike point sensors, they can measure and provide a continuous spatial distribution of a physical quantity, effectively creating a mapped profile of the parameter of interest. A well-known example is RADAR, and more recently, its optical counterpart, LIDAR, which offer a spatial distribution of reflections along their line of sight.

One often overlooked yet powerful application of optical fibers is their capability to function as distributed sensors, leveraging the inherent scattering properties of silica glass (SiO_2), the primary material used in fiber construction. In their most common implementation, known as Optical Time-Domain Reflectometry (OTDR), an intense light pulse is launched into the optical fiber, where it scatters continuously along its propagation. A small fraction of this scattered light—roughly 1/600th in standard single-mode fibers—is coupled back toward the source, providing a continuous time-domain distribution that, when calibrated, yields position-resolved information (Hartog, 2017). This functionality is derived from the predictable velocity of light within the fiber.

A key advantage of optical fibers lies in their exceptionally low propagation loss, enabling measurements over tens of kilometers. However, this benefit is offset by the inherently weak intensity of scattered light and the minuscule fraction that is returned in the backward direction. This trade-off necessitates balancing several parameters. For example, increasing the pulse energy by making it longer enhances the scattered power but comes at the cost of reduced spatial resolution, as longer pulses cover broader sections of the fiber. Conversely, shorter pulses provide finer spatial resolution but result in diminished scattered power and reduced sensing range due to exponential power decay along the fiber.

Ultimately, the system's performance is determined by its signal-to-noise ratio (SNR). This article assesses the theoretical performance limits of distributed sensors based on the state-of-the-art techniques available today for various types of scattering phenomena. It also explores opportunities to enhance these capabilities through innovative approaches and questions the integration of artificial intelligence to optimize performance.

2 Expected ultimate performance by sensor type

This section evaluates the performance limits of various distributed optical fiber sensors under specific conditions, for the sake of a fair comparison: a long-distance range (>30 km), spatial resolution of 1 m, temperature uncertainty of approximately 1 K, and a total measurement time between 1 and 60 s. Systems with relaxed constraints, such as shorter distance ranges, worse spatial resolution or longer averaging times, can achieve better performance than those outlined here.

2.1 Raman-based sensors

Raman-based distributed fiber sensors are widely adopted due to their simple, robust optical configurations and relatively low implementation costs. Raman scattering arises from changes in electrical permittivity caused by molecular vibrations, with its amplitude governed by the number of phonons. The scattered spectrum consists of two broad bands—one shifted to shorter wavelengths (Anti-Stokes) and the other to longer wavelengths (Stokes)—relative to the incident light. At a wavelength of 1,550 nm, commonly used for its minimal optical loss in silica, this spectral shift is approximately 90 nm.

The sensing principle leverages the temperature dependence of the Anti-Stokes signal intensity, dictated by the Bose-Einstein distribution in this pure thermally-activated process. At room temperature, the energy shift ($h\Delta\nu$) exceeds the thermal energy ($k_B T$), making the Anti-Stokes signal highly sensitive to temperature (h and k_B being Planck's, respectively Boltzmann's, constants). In contrast, the Stokes signal is only marginally temperature-dependent since a phonon is always created in the process, independently of temperature. By comparing the intensities of these two bands, an exponential relationship with temperature can be exploited for sensing (Dakin et al., 1985; Farahani and Gogolla, 1999).

Although Raman scattering is spectrally broad and incoherent, it offers advantages such as loose requirements for the spectral purity of incident pulses. Peak powers of several watts can be employed without concerns about nonlinear effects like modulation instability. However, the inability to use coherent detection reduces sensitivity.

For Anti-Stokes scattering, the backscatter factor (k_{AS}) - giving the amount of back-coupled scattered power in the fiber for a given incident pulse energy - is approximately 0.0075 W/J in a standard single-mode fiber at 1,550 nm (Bolognini and Hartog, 2013). For a pulse with 1 W peak power and 10 ns duration (corresponding to a 1 m spatial resolution), only 75 pW of backscattered power is collected at the fiber's near end. At a distance of 10 km, this power drops to 20 pW, and at 50 km, it is reduced to a mere 0.075 pW, yet equivalent to a photon flux of 500,000 photons per second.

State-of-the-art InGaAs PIN photoreceivers have a noise power of 25 nW over the 70 MHz bandwidth required for 1 m spatial resolution. This background noise is several orders of magnitude higher than the detected signal (~350 times greater near the fiber's input end). To achieve a 10 dB SNR, the noise must be reduced through averaging by a factor of approximately 10^6. However, for long fibers, the pulse repetition rate is limited to 1 kHz by the roundtrip light propagation time, resulting in a minimum acquisition time of 1,000 s—far exceeding the desired maximum of 60 s. Thus, standard Raman-based systems require additional enhancements to meet performance goals.

One improvement involves replacing the PIN photoreceiver with an InGaAs avalanche photodiode (APD), which provides an internal gain of approximately 10. This reduces the required averaging time by a factor of 100, enabling a 10-s acquisition time. For a 60-s acquisition, the signal can tolerate a reduction of 2.45 times due to propagation loss, allowing a sensing distance of ~6.5 km. This performance aligns with commercially available Raman sensors.

Additional sophistication can be introduced through coding techniques. Instead of launching isolated pulses, successive but distinct sequences of pulses sequence of pulses can be used, designed to retrieve an equivalent single-pulse response through linear operations (Bolognini and Hartog, 2013; Park et al., 2006). For a N-pulse sequence the coding gain is $\sim\sqrt{N}/2$, that can be viewed like an equivalent amplification of the pulse. A sequence length of 256 pulses provides an 11-fold coding gain, equivalent to 17.4 km of additional sensing range.

Combining APD detection with coding enables sensing over ~25 km with 1 m spatial resolution, albeit with a highly complex system. The ultimate enhancement involves photon-counting detection, which theoretically achieves the shot noise limit (Bolognini and Hartog, 2013; Lauber et al., 2018). Despite practical limitations—such as reduced quantum efficiency (~10%) and dead time after each event—photon counting could enable sensing distances of up to 55 km, probably beyond the target of a one-minute measurement time.

2.2 Brillouin-based sensors

Brillouin-based sensors have matured significantly over the past decade and are widely used in field applications requiring long-distance coverage and robustness against environmental perturbations. Unlike Raman sensors, Brillouin sensors derive information from spectral shifts in the scattered light, rather than intensity changes, which significantly enhances robustness.

Brillouin scattering arises from the interaction of light with periodic refractive index variations induced by classical acoustic vibrations in the fiber. This interaction results in a highly narrow spectrum (~30 MHz) and a frequency shift proportional to the temperature-dependent acoustic velocity in silica. For example, the Brillouin frequency shift changes by approximately 1 MHz per Kelvin, necessitating precise frequency control during signal analysis. This precision is achieved using electro-optic modulators to generate stable, finely tunable demodulation signals (Nikles et al., 1997).

The coherence requirements of Brillouin scattering impose strict limitations on the spectral purity of incident pulses. Nonlinear effects, such as modulation instability, further constrain the peak pulse power. In standard single-mode fibers, the peak power is limited to ~100 mW for long distances (>20 km) (Alem et al., 2015). Dispersion-shifted fibers with normal dispersion are immune to modulation instability, but are still restricted by other nonlinear effects, such as stimulated forward Raman scattering, and eventually allow only slightly higher peak powers (~120 mW) (Foaleng et al., 2011).

2.2.1 Spontaneous Brillouin scattering sensing

Spontaneous Brillouin sensors operate similarly to Raman sensors but exhibit much weaker temperature dependence due to the high density of thermally excited phonons at ambient conditions. Consequently, the Stokes and Anti-Stokes scattered intensities do not differ significantly and the temperature is solely retrieved from the frequency shift of the lines.

The backscatter factor for spontaneous Brillouin scattering (k_B) is approximately 0.0616 W/J, an order of magnitude higher than Raman scattering (Boyd, 2003; Jin et al., 2024). However, the stricter power limitations imposed by nonlinear effects counteract this advantage (Alem et al., 2015). For a 100 mW peak pulse and 10 ns duration, only 62 pW of backscattered power is detected near the fiber input.

Unlike Raman scattering, the narrow spectral bandwidth of Brillouin scattering enables coherent detection, which is essential for extracting the spectral shift with high resolution (1 MHz). By employing a strong local oscillator, the signal-to-noise ratio can theoretically approach the shot noise limit. With coherent detection, the noise power for a 1 m spatial resolution system is approximately 37 pW over a 70 MHz bandwidth.

To achieve a complete Brillouin spectral analysis, 100 frequency-incremented traces are typically required. Averaging each trace 64 times over a total acquisition time of 60 s yields an 11 dB signal-to-noise ratio, sufficient for sensing up to 3 km of fiber.

Further improvements can be achieved through coding techniques, as with Raman sensors (Soto et al., 2008). Coding allows an additional sensing distance of ~17 km, resulting in a total range of 20 km with a 1 m spatial resolution. APDs bring no benefit in the shot noise detection limit since the extra noise is roughly equivalent to the internal gain for an InGaAs APD.

2.2.2 Stimulated Brillouin scattering sensing

Stimulated Brillouin scattering (SBS) introduces a nonlinear coupling between an incident pulse and a counterpropagating continuous-wave probe. This coupling occurs when the frequency difference between the two waves satisfies the phase-matching condition for Brillouin scattering, typically in the 10–11 GHz range. The probe signal experiences a gain, enabling temperature retrieval by scanning the frequency difference to determine the peak gain frequency proportional to the acoustic velocity.

The strength of this interaction is characterized by the Brillouin gain coefficient (γ_B), which is ~4×10^7 1/J for silica fibers (Nikles et al., 1997). For a 100 mW, 10 ns pulse, this interaction yields a 4% gain in the probe power. However, the probe power is practically limited to ~300 μW to prevent distortion from input pulse depletion (Thévenaz et al., 2013).

With these constraints, the maximum signal power contrast due to gain is ~12 μW, while the noise is dominated by the full probe power of 312 μW. This power enables a shot noise limit detection and the attenuated signal after propagation over several tens of km along the fiber can be restored to the shot noise limit detection with simple optical preamplification (Wang et al., 2020). Taking some margin due to amplifier noise, the noise power over a 70 MHz bandwidth is approximately 0.2 μW. With 64-fold averaging during a 60-s acquisition, this noise is reduced to 25 nW, allowing for a tolerable gain reduction from propagation loss. This enables sensing over 90 km with a 10 dB signal-to-noise ratio.

Additional coding techniques can extend this range by another 17 km, enabling sensing over distances exceeding 100 km (Soto et al., 2010).

2.3 Rayleigh-based sensors

Rayleigh scattering is a spontaneous elastic process that arises from thermodynamic density fluctuations frozen into the silica structure during fiber manufacturing (Boyd, 2003). These density fluctuations lead to refractive index variations, which cause phase shifts in the scattered light. Since the fluctuations are random, the backscattered light exhibits random interference, producing a jagged intensity pattern that resembles noise and the scattered intensity follows an exponential probability distribution (Koyamada et al., 2009).

A key advantage of Rayleigh scattering is its stationary nature: under identical conditions (e.g., fixed wavelength and temperature), the interference pattern remains unchanged and consistent. However, when temperature or strain changes, the refractive index shifts, altering the phase and the resulting intensity pattern. This allows Rayleigh-based sensors to detect temperature or strain variations with high sensitivity (Koyamada et al., 2009). The phase shifts induced by refractive index changes can be compensated by proportional frequency adjustments, with a temperature change of 1 K corresponding to a 1.3 GHz frequency shift.

Traces are collected at different optical frequencies spanning several tens of GHz. Initially, a set of reference traces is acquired under known conditions (e.g., uniform temperature), with each trace corresponding incrementally to a specific frequency. This allows the spectral distribution at each position to be determined, typically forming a jagged distribution as well (Liokumovich et al., 2015). Traces obtained under unknown conditions are then processed in the same manner, and the equivalent frequency shift at each position is calculated by finding the spectral shift giving the maximum correlation between the measured and the reference spectral distributions at those positions. This method achieves extreme temperature sensitivity—three orders of magnitude greater than that of Brillouin sensors.

Since the measuring principle relies on interference, the light must remain strictly coherent during the incident pulse duration. Consequently, the same power limitations that apply to Brillouin sensors are also relevant here. The backscattering coefficient is significantly higher than for inelastic scattering processes, at 5 W/J (Bolognini and Hartog, 2013). For a typical pulse of 100 mW and 10 ns duration, the backscattered power at the near fiber end is approximately 5 nW. Considering that the equivalent thermal noise power for direct detection is 25 nW, averaging is required to achieve a 10 dB signal-to-noise ratio (SNR). However, the averaging must be limited to 64 iterations to maintain a total measurement time of about 1 min, due to the need for a frequency scan similar to that in Brillouin sensing. This averaging reduces the noise level to 3 nW, which is still insufficient to ensure a 10 dB SNR. Additional measures are needed to achieve acceptable performance.

The simplest and most straightforward solution is to amplify the backscattered signal optically before detection. Standard optical amplification of 30 dB increases the signal power to 5 μW, which remains below the shot noise limit for standard photodetectors. As a result, the noise contribution from the amplifier is negligible compared to thermal noise. With a noise power of 3 nW after averaging, this provides a comfortable 32 dB SNR, allowing for up to 22 dB of light attenuation while maintaining a 10 dB SNR. This corresponds to a sensing range of 55 km.

Due to the nonlinear relationship between phase and intensity, coherent Rayleigh sensing cannot currently benefit from coding techniques. However, coherent detection can be employed to reach the shot noise limit, enabling a 10 dB SNR with a signal power as low as ~2 nW, without requiring averaging. If averaging is applied, an additional 20 dB margin becomes available, enabling a potential sensing range extension of 50 km. By combining optical amplification with coherent detection, a total sensing range of up to 105 km can be achieved.

It is also worth noting that an additional stage of optical amplification can provide a similar improvement in SNR, leading to a comparable extension of the sensing range.

3 Discussion and perspectives

The performance estimates presented in this article are not precise predictions but provide a scalable framework for assessing the feasibility and limitations of various distributed optical fiber sensing technologies.

Due to the exponential signal decay caused by propagation losses, the sensing range and resolution of these systems are primarily governed by the signal-to-noise ratio (SNR) (Soto and Thévenaz, 2013). Among the techniques discussed, stimulated Brillouin scattering and coherent Rayleigh scattering emerge as the most promising for achieving sensing distances exceeding 50 km, even with straightforward implementations that rely on leveling the detected signal by optical amplification. With advanced techniques, such as coding or multi-stage amplification, these ranges can extend to ~100 km, surpassing the capabilities of Raman and spontaneous Brillouin sensing.

3.1 Challenges and opportunities

The critical factor for improving distributed sensing systems is increasing the SNR (Soto and Thévenaz, 2013). However, the energy of the incident signal is constrained by material limitations of silica fibers and nonlinear effects. Most advanced signal processing techniques, such as coding and coherent detection, have already been optimized (Sun et al., 2020). Future efforts must focus on:

3.1.1 Enhancing scattering efficiency

The scattering factor could be increased by introducing tailored modifications to the fiber. One promising approach is printing ultra-weak fiber Bragg gratings along the fiber length to enhance backscattering for a given pulse energy (Thévenaz et al., 2014). While these methods have shown success in niche (Westbrook et al., 2017), short-distance applications, further development is required to adapt them for long-range sensing.

3.1.2 Reducing propagation loss

Decreasing the fiber's propagation loss directly enhances sensing range. A halving of the loss doubles the range, highlighting the potential of emerging hollow-core antiresonant fibers (Poletti, 2014). These fibers exhibit ultra-low losses and significantly higher thresholds for nonlinear distortion, allowing for the use of higher pulse energies without compromising spatial resolution. Recent studies have demonstrated losses lower than those of conventional solid silica fibers (Chen et al., 2024) and the feasibility of distributed Brillouin sensing in gas-filled hollow-core fibers (Yang et al., 2020), with improved scattering factors and temperature sensitivity, even at cryogenic temperatures (Yang et al., 2023). Note that Rayleigh scattering sensing is unpracticable in hollow-core antiresonant fibers, as the reduction in propagation loss in these fibers is achieved by minimizing Rayleigh scattering itself.

3.1.3 Leveraging artificial intelligence

Distributed fiber sensors generate vast amounts of data, making them ideal candidates for integration into big data systems. While traditional analytical methods are highly effective for extracting temperature and strain distributions, artificial intelligence (AI) could play a transformative role in optimizing data acquisition, interpreting stochastic signals (e.g., coherent Rayleigh responses), and accelerating decision-making processes (Shiloh et al., 2019; Venketeswaran et al., 2022; Kandamali et al., 2022). It has already demonstrated significant potential for detecting and interpreting seismic data, as well as estimating pipeline corrosion by analyzing the acoustic noise generated by liquid flow (Tejedor et al., 2017). These complex, indirect responses are challenging to interpret using traditional signal processing methods. However, machine learning proves highly effective, leveraging its ability to process and analyze vast amounts of data with remarkable accuracy.

3.2 The path forward

The future of distributed optical fiber sensing lies in its ability to provide detailed spatial and temporal insights across increasingly larger scales. Innovations in fiber materials, signal processing, and AI-driven analytics hold immense potential to overcome the current limitations of these systems. By addressing key challenges, distributed fiber sensors can further their contributions to resource optimization, environmental monitoring, and system safety.

Keeping pace with the rapid development of hollow-core fibers, advanced coding techniques, and AI-based analytics is crucial. These advancements could redefine the practical limits of distributed fiber sensing, unlocking new opportunities for improving infrastructure reliability, environmental protection, and operational efficiency, for a better use of resources and a safer environment.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

LT: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Alem, M., Soto, M. A., and Thévenaz, L. (2015). Analytical model and experimental verification of the critical power for modulation instability in optical fibers. *Opt. Express* 23 (23), 29514–29532. doi:10.1364/OE.23.029514

Bolognini, G., and Hartog, A. (2013). Raman-based Fibre sensors: trends and applications. *Opt. Fiber Technol.* 19 (6), 678–688. doi:10.1016/j.yofte.2013.08.003

Boyd, R. W. (2003). *Nonlinear optics*. New York: Academic.

Chen, Y., Petrovich, M. N., Numkam Fokoua, E., Adamu, A. I., Hassan, M. R. A., Sakr, H., et al. (2024). "Hollow core DNANF optical fiber with <0.11 dB/km loss," in *Optical fiber communication conference (OFC) 2024, Th4A.8* (San Diego California: Optica Publishing Group). doi:10.1364/OFC.2024.Th4A.8

Dakin, J. P., Pratt, D. J., Bibby, G. W., and Ross, J. N. (1985). Distributed optical Fibre Raman temperature sensor using a semiconductor light source and detector. *Electron. Lett.* 21 (13), 569–570. doi:10.1049/el:19850402

Farahani, M. A., and Gogolla, T. (1999). Spontaneous Raman scattering in optical fibers with modulated probe light for distributed temperature Raman remote sensing. *J. Light. Technol.* 17 (8), 1379–1391. doi:10.1109/50.779159

Foaleng, S. M., and Thévenaz, L. (2011). "Impact of Raman scattering and modulation instability on the performances of Brillouin sensors," Proc. SPIE 7753, 21st International Conference on Optical Fiber Sensors, May 19, (Bellingham, WA). 77539. doi:10.1117/12.885105

Hartog, A. H. (2017). *An introduction to distributed optical Fibre sensors*. 1st ed. Boca Raton: CRC Press. doi:10.1201/9781315119014

Jin, S., Yang, Z., Hong, X., and Wu, J. (2024). Analytical signal-to-noise ratio model on frequency-scanned Brillouin optical time-domain Reflectometry. *J. Light. Technol.* 42, 5786–5796. doi:10.1109/JLT.2024.3398634

Kandamali, D. F., Cao, X., Tian, M., Jin, Z., Dong, H., and Yu, K. (2022). Machine learning methods for identification and classification of events in ϕ -OTDR systems: a review. *Appl. Opt.* 61 (11), 2975. doi:10.1364/AO.444811

Koyamada, Y., Imahama, M., Kubota, K., and Hogari, K. (2009). Fiber-optic distributed strain and temperature sensing with very high measurand resolution over long range using coherent OTDR. *J. Light. Technol.* 27 (9), 1142–1146. doi:10.1109/JLT.2008.928957

Lauber, T., Cedilnik, G., and Lees, G. (2018). "Physical limits of Raman distributed temperature sensing - are we there yet?," in 26th international Conference on optical fiber sensors, *WF30* (Lausanne: OSA). doi:10.1364/OFS.2018.WF30

Liokumovich, L. B., Ushakov, N. A., Kotov, O. I., Bisyarin, M. A., and Hartog, A. H. (2015). Fundamentals of optical fiber sensing schemes based on coherent optical time domain Reflectometry: signal model under static fiber conditions. *J. Light. Technol.* 33 (17), 3660–3671. doi:10.1109/JLT.2015.2449085

Nikles, M., Thévenaz, L., and Robert, P. A. (1997). Brillouin gain spectrum characterization in single-mode optical fibers. *J. Light. Technol.* 15 (10), 1842–1851. doi:10.1109/50.633570

Park, J., Bolognini, G., Lee, D., Kim, P., Cho, P., Di Pasquale, F., et al. (2006). Raman-based distributed temperature sensor with simplex coding and link optimization. *IEEE Photonics Technol. Lett.* 18 (17), 1879–1881. doi:10.1109/LPT.2006.881239

Poletti, F. (2014). Nested antiresonant nodeless hollow core fiber. *Opt. Express* 22 (20), 23807. doi:10.1364/OE.22.023807

Shiloh, L., Eyal, A., and Raja, G. (2019). Efficient processing of distributed acoustic sensing data using a deep learning approach. *J. Light. Technol.* 37 (18), 4755–4762. doi:10.1109/JLT.2019.2919713

Soto, M. A., Bolognini, G., and Di Pasquale, F. (2008). Analysis of optical pulse coding in spontaneous brillouin-based distributed temperature sensors. *Opt. Express* 16 (23), 19097. doi:10.1364/OE.16.019097

Soto, M. A., Bolognini, G., Di Pasquale, F., and Thévenaz, L. (2010). Long-range Brillouin optical time-domain analysis sensor employing pulse coding techniques. *Meas. Sci. Technol.* 21 (9), 094024. doi:10.1088/0957-0233/21/9/094024

Soto, M. A., and Thévenaz, L. (2013). Modeling and evaluating the performance of Brillouin distributed optical fiber sensors. *Opt. Express* 21 (25), 31347–31366. doi:10.1364/OE.21.031347

Sun, X., Yang, Z., Hong, X., Zaslawski, S., Wang, S., Soto, M. A., et al. (2020). Genetic-optimised aperiodic code for distributed optical Fibre sensors. *Nat. Commun.* 11, 5774. doi:10.1038/s41467-020-19201-1

Tejedor, J., Macias-Guarasa, J., Martins, H., Pastor-Graells, J., Corredera, P., and Martin-Lopez, S. (2017). Machine learning methods for pipeline surveillance systems based on distributed acoustic sensing: a review. *Appl. Sci.* 7 (8), 841. doi:10.3390/app7080841

Thévenaz, L., Chin, S., Sancho, J., and Sales, S. (2014). Novel technique for distributed Fibre sensing based on faint long gratings (FLOGs). *Proc. SPIE 9157:Paper 91576W. SPIE* 9157, 91576W. doi:10.1117/12.2059668

Thévenaz, L., Mafang, S. F., and Lin, J. (2013). Effect of pulse depletion in a Brillouin optical time-domain analysis system. *Opt. Express* 21 (12), 14017–14035. doi:10.1364/OE.21.014017

Venketeswaran, A., Lalam, N., Wuenschell, J., Ohodnicki, P. R., Badar, M., Chen, K. P., et al. (2022). Recent advances in machine learning for fiber optic sensor applications. *Adv. Intell. Syst.* 4 (1), 2100067. doi:10.1002/aisy.202100067

Wang, S., Yang, Z., Soto, M. A., and Thévenaz, L. (2020). Study on the signal-to-noise ratio of Brillouin optical-time domain analyzers. *Opt. Express* 28 (14), 19864–19876. doi:10.1364/OE.393928

Westbrook, P. S., Kremp, T., Feder, K. S., Ko, W., Monberg, E. M., Wu, H., et al. (2017). Continuous multicore optical fiber grating arrays for distributed sensing applications. *J. Light. Technol.* 35 (6), 1248–1252. doi:10.1109/JLT.2017.2661680

Yang, F., Gyger, F., and Thévenaz, L. (2020). Intense Brillouin amplification in gas using hollow-core waveguides. *Nat. Photonics* 14 (11), 700–708. doi:10.1038/s41566-020-0676-z

Yang, Y., Soto, M. A., and Thévenaz, L. (2023). "Novel low-temperature fiber sensing technique using Brillouin scattering in gas," in 28th international Conference on optical fiber sensors, *F2.3. Naka-Ku, hamamatsu-shi* Washington, DC: (Optica Publishing Group). doi:10.1364/OFS.2023.F2.3