Big data on the horizon from a new generation of distributed optical fiber sensors

Cite as: APL Photonics **5**, 020401 (2020); https://doi.org/10.1063/1.5144123
Submitted: 31 December 2019 . Accepted: 31 December 2019 . Published Online: 03 February 2020

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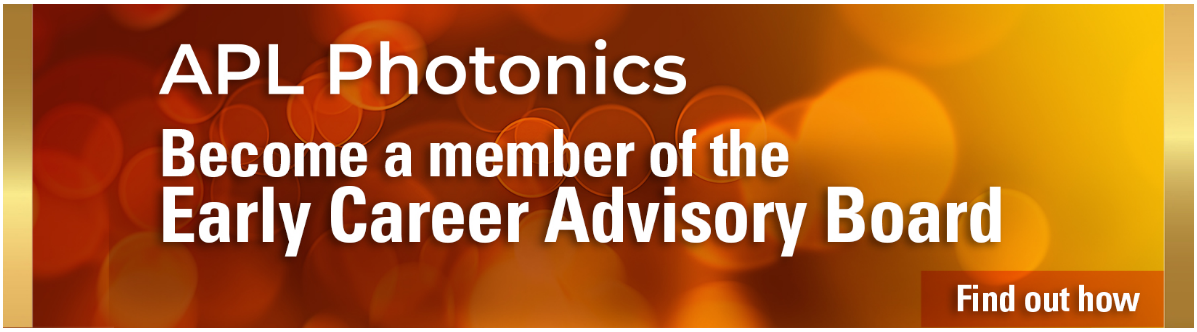

APL Photonics EDITORIAL scitation.org/journal/app

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It has been more than 40 years since the first demonstrations of a new class of optical sensor enabled by long lengths of low loss optical fibers. These included acoustic sensors, gyroscopes, and distributed temperature and strain sensing as well as various fiber coupled transducers that extended fiber sensitivity to other applications such as measurement of pressure and magnetic fields.[1] Only a decade later, during the 1980s the first proposals to use fiber Bragg gratings (FBGs) as strain and temperature sensors within lengths of fiber were made.[2] In the years following these innovations, this first generation of optical fiber technologies was commercialized and is now found throughout many industries, including aerospace, defense, security, civil engineering, and the oil and gas industry. Today, optical fiber sensors comprise a $1 billion global market.[3]

As this first generation of optical fiber sensors has reached maturity, more recent developments in photonics have resulted in the possibility of a new generation of distributed optical fiber sensors. Critical to these advances is the ability to measure phase and coherent properties of light scattered through long lengths of optical fibers. As with the previous generation of distributed sensors, developments in optical fiber telecommunications has helped enable the next generation of sensors. Key innovations have been the development of improved distributed interrogation techniques such as Optical Frequency Domain Reflectometry (OFDR) and coherent Optical Time Domain Reflectometry (OTDR) suitable for Distributed Acoustic vibration Sensing (DAS). Over the past two decades, the improvements in these techniques have been combined with innovations in sensor fibers such as twisted multicore fiber and fiber with continuously enhanced scattering over kilometer lengths. The combination of these technologies has led to sensing modalities that go beyond the earlier sensor types. These include optical fiber shape sensing and precise, phase sensitive distributed acoustic sensing over many kilometers.

A common thread in these methods is the enormous volume of data that can be collected from continuous distributed fiber sensors. This has led to the demand for new algorithms to convert this data into useful sensing signals. In analogy with the extensive use of deep learning and artificial intelligence methods used with various imaging technologies, these new sensors will drive the development of new algorithms from the data science community. More generally, the use of next generation sensor interrogators and enhanced optical fiber sensors has led to the possibility of accumulating vast, real-time databases of acoustic and other measurands throughout fiber networks and within industrial and medical settings that use optical fiber. These developments promise significant impact on applications such as the design of future smart cities and a global “internet of things” (IoT), which will bring even more widespread use of distributed fiber sensing.[4–6] As part of this trend there is increased interest in the merging of multiple sensor inputs, or multisensor fusion, using machine learning and other data science techniques, to provide meaningful data for prediction and control within complex systems.[7–9] Such sensor fusion algorithms will also benefit from the wealth of data offered by distributed optical fiber sensors.

Two distributed sensing applications stand out in this context. The first is optical fiber shape sensing, which acts over meters of fiber, and the second is distributed acoustic sensing (DAS), which acts over many kilometers of fiber. Both methods rely on elastic optical backscattering signals, and in both methods significant improvements have been made possible with enhanced sensing fibers and interrogators.

In optical fiber shape sensing the goal is to reconstruct the entire shape of an optical fiber using only the optical signals backscattered from light propagating in the fiber cores.[10–12] Shape reconstruction has great potential in many applications, including medical, industrial, and structural health monitoring. Since the fiber is passive, biocompatible, and immune to electromagnetic interference, it has great utility for many medical applications. The trend toward high precision robotic surgical procedures is a key driver for shape sensing. Fiber shape sensing promises to revolutionize medical instrument use because of its ability to track the precise location of medical instruments inserted into the body during noninvasive surgery,[13,14] and sensor fusion algorithms that combine fiber sensors and traditional ultrasound inputs using data science techniques such as convolutional neural networks are being discussed.[15] Moreover, with the increased interest in medical applications that have multimodal functionality, adding instrument shape to the set of measurements will allow guidance, position, force measurement, and even the measurement of fine scale texture.

While conventional discrete fiber Bragg grating arrays have been applied to this demanding task, such arrays have limited spatial resolution and are typically limited to a small number (10–20) of sensing points determined by wavelength division multiplexing within the telecom C and L bands. As a result, the older generation of FBG arrays are limited to sensing of bend and force over relatively short lengths of fiber, and there has been demand for a new generation of fibers suitable for shape sensing.

Rigorous, full shape reconstruction requires knowledge of the local bend and twist along the fiber with high resolution.[10,12,16] The local state of bend and twist of an optical fiber can be obtained from measurements of the axial strain across the fiber cross section. As a result, shape sensing requires the use of multicore optical fiber. Measurements of axial strain must be made in four or more fiber cores along the entire length of the fiber. Moreover, the outer cores of the optical fiber must twist around the center core in order for the fiber to be sufficiently sensitive to local twist. The typical spatial resolution required for shape reconstruction is less than 1 mm. For typical lengths of optical fiber of 1 m or more, a single core has more than 1000 points, far beyond the capabilities of traditional FBG sensing arrays.

The interrogation technique that allows for such high density sensing is very different from traditional intensity based spectral interrogation used with Bragg grating arrays where only discrete points can be measured. To obtain nearly continuous high resolution measurements along the fiber cores, the interrogators use swept wavelength interferometry (SWI), also known as optical frequency domain reflectometry (OFDR). This method is similar to that used in optical coherence tomography imaging. However, because the light is guided in a fiber core, it is possible to make precise, high resolution measurements over lengths in excess of 10 m. Telecom band tunable laser technology has been adapted to fulfill the requirement of a narrow linewidth, precisely tunable source. Significant development over the past two decades has given rise to OFDR devices that have spatial resolution down to 10 μm along an optical fiber core (see for instance the LUNA, Inc. OBR). While such measurements may be applied directly to Rayleigh backscattering, greatly improved system performance can be achieved if a continuous weak grating is inscribed along the length of the fiber core.[16] In effect, the OFDR technique converts a continuous grating into an array of sensors with a sensor length set by the OFDR bandwidth. Figure 1 shows a schematic image of the resulting twisted multicore optical fiber. Also shown is an illustration of the shape reconstruction of an optical fiber twisted around a post.

For sensing systems operating over kilometer lengths, Distributed Acoustic Sensing (DAS) is showing significant promise and has also undergone a significant degree of development over the past 20 years.[17,18] In DAS, the entire optical fiber, sometimes as long as 40 km, can turn into an acoustic sensor or extended microphone. As with OFDR, recently developed techniques can efficiently record phase sensitive measurements of backscattered light. Instead of the frequency domain, DAS performs phase sensitive measurements in the time domain. Such OTDR measurements are well known from fiber telecom systems and are used to measure fiber attenuation and the locations of discrete losses in the fiber. In coherent OTDR, the pulses are modulated and carved from a very stable, low phase noise, low linewidth laser, typically with linewidths less than 100 kHz. Successive pulses are compared with either optical or digital methods to obtain the evolution of optical phase or pathlength along the fiber as a function of time. Differential measurements between pairs of pulses can then give a snapshot of any acoustic disturbance along the entire optical fiber. With modern interrogators, such DAS systems have been made sufficiently sensitive to measure automobile and foot traffic, trains, and other disturbances near the optical fiber. Recent measurements have shown that an entire optical fiber telecommunications network can be transformed into a wide area sensor of any disturbance near the telecom fibers.[19] In other applications, it has been shown that such systems can measure seismic disturbances. Such applications can have a significant impact on discovery and management of oil and gas reservoirs as well as the maintenance of wells and pipes that service these assets.[20] DAS has even been shown to be sensitive enough to measure earthquakes.[21]

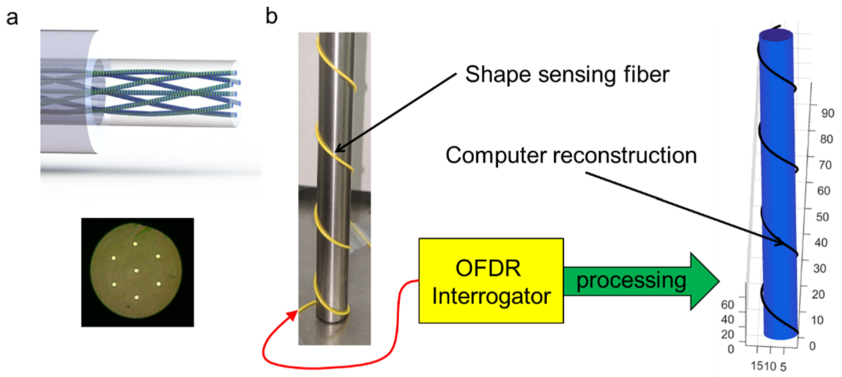

FIG. 1. Fiber shape sensing: Distributed sensing of more than 4000 points per meter of fiber. (a) Specially designed twisted multicore fiber with continuous weak gratings in all cores that allow for rapid high precision shape sensing. (b) Demonstration of shape reconstruction of a fiber (yellow) wrapped around a post (left) using OFDR interrogation. The reconstructed shape is shown on the right.

Much like OFDR applications, DAS applications benefit greatly from an increase in optical signal to noise ratio. As with shape sensing, it is possible to treat optical fibers with ultraweak exposures to increase the backscattering signal substantially. The resulting signal to noise in the acoustic domain can be increased by more than an order of magnitude.[22] Such enhanced scatter fibers have the potential to open new areas of sensing. The possibility of monitoring structural health of buildings, pipelines, rail links, and other critical linear assets promises to be a critical component of future smart cities. Moreover, the increased signal to noise of these next generation acoustic sensing fibers promises to greatly decrease the cost of the optical interrogation methods used in DAS as well as allow wide field sensing that may be transformative in seismic sensing and monitoring of earthquakes.

At the same time that distributed sensing technologies like DAS and shape sensing become more mature, there has been increasing interest in the application of advanced tools of data science in photonics, particularly for imaging.[23] These trends hold promise for a host of new applications in distributed sensing as well.[24–26] Distributed sensing can generate enormous volumes of real time data. The number of sensing points in a single strand of distributed sensor fiber can exceed 1000, and readout speeds for the entire system can exceed 1 kHz. Reducing this data to meaningful sensor outputs requires many layers of analysis. Detector outputs must be converted into phase and then to strain variations in time and space. The use of enhanced fibers makes this analysis significantly more tractable. However, as such systems become more complex at various levels of analysis, data processing approaches that use deep learning techniques promise to bring still greater efficiency. Practical applications will require the reduction of gigabytes of data per second into recognizable events such as gas leaks, car traffic, structural health, shape change of surgical devices, security intrusions, and even signs of impending earthquakes. The full potential of distributed fiber sensing will be realized when a new set of machine learning and data fusion techniques are successfully applied to these new data. This interdisciplinary challenge will bring together the fields of photonics and data science in new ways to solve real world problems.

Enhanced distributed sensing systems will play a key role in sensing of linear assets and medical systems throughout many applications and industries. The emerging research on the use of data science in sensing promises a new generation of sensors that will enable systems from robotic surgery to smart cities and the internet of things. As the photonics research community embraces approaches such as machine learning and artificial intelligence to analyze complex optical data, a new set of tools for distributed fiber optic sensing will emerge. APL Photonics is a cross-disciplinary journal that is ideally suited to researchers publishing in this area of research. The editorial team is excited about receiving your contributions to the fast growing body of work on the fusion of data science and photonics.

REFERENCES

[1] T. G. Giallorenzi, J. A. Bucaro, A. Dandridge, G. H. Sigel, J. H. Cole, S. C. Rashleigh, and R. G. Priest, "Optical fiber sensor technology," IEEE Trans. Microwave Theory Tech. **30**(4), 472–511 (1982).

[2] G. Meltz, J. R. Dunphy, W. H. Glenn, J. D. Farina, and F. J. Leonberger, "Fiber optic temperature and strain sensors," Proc. SPIE **798**, 104–114 (1987).

[3] See, e.g., http://www.igigroup.com/st/pages/photonic_sensor_report.html#Anchor-Overview-17691 for "2019 distributed and single point fiber optic sensing systems forecast—A photonic sensor consortium market survey report" produced by Light Wave Venture LLC, March 2019.

[4] G. P. Hancke and G. P. Hancke, Jr., "The role of advanced sensing in smart cities," Sensors **13**(1), 393–425 (2013).

[5] K. Bremer, F. Weigand, Y. Zheng, L. Alwis, R. Helbig, and B. Roth, "Structural health monitoring using textile reinforcement structures with integrated optical fiber sensors," Sensors **17**(2), 345 (2017).

[6] F. Tao, Y. Zuo, L. Da Xu, and L. Zhang, "IoT-based intelligent perception and access of manufacturing resource toward cloud manufacturing," IEEE Trans. Ind. Inf. **10**(2), 1547–1557 (2014).

[7] R. Gravina, P. Alinia, H. Ghasemzadeh, and G. Fortino, "Multi-sensor fusion in body sensor networks: State-of-the-art and research challenges," Inf. Fusion **35**, 68–80 (2017).

[8] M. Wang, C. Perera, P. P. Jayaraman, M. Zhang, P. Strazdins, R. K. Shyamsundar, and R. Ranjan, "City data fusion: Sensor data fusion in the internet of things," Int. J. Distrib. Syst. Technol. **7**(1), 15–36 (2016).

[9] H. Xing, F. Li, H. Xiao, Y. Wang, and Y. Liu, "Ground target detection, classification, and sensor fusion in distributed fiber seismic sensor network," in *Advanced Sensor Systems and Applications III* (International Society for Optics and Photonics, 2007), Vol. 6831, p. 683015.

[10] R. G. Duncan, M. E. Froggatt, S. T. Kreger, R. J. Seeley, D. K. Gifford, A. K. Sang, and M. S. Wolfe, "High-accuracy fiber-optic shape sensing," Proc. SPIE **6530**, 65301S (2007).

[11] C. G. Askins, G. A. Miller, and E. J. Friebele, "Bend and twist sensing in a multiple-core optical fiber," in *Optical Fiber Communication Conference/National Fiber Optic Engineers Conference, OSA Technical Digest (CD)* (Optical Society of America, 2008), paper OMT3.

[12] J. P. Moore and M. D. Rogge, "Shape sensing using multi-core fiber optic cable and parametric curve solutions," Opt. Express **20**(3), 2967–2973 (2012).

[13] R. J. Roesthuis, M. Kemp, J. J. van den Dobbelsteen, and S. Misra, "Three-dimensional needle shape reconstruction using an array of fiber Bragg grating sensors," IEEE/ASME Trans. Mechatron. **19**(4), 1115–1126 (2013).

[14] C. Shi, X. Luo, P. Qi, T. Li, S. Song, Z. Najdovski, T. Fukuda, and H. Ren, "Shape sensing techniques for continuum robots in minimally invasive surgery: A survey," IEEE Trans. Biomed. Eng. **64**(8), 1665–1678 (2016).

[15] A. Denasi, F. Khan, K. J. Boskma, M. Kaya, C. Hennersperger, R. Göbl, M. Tirindelli, N. Navab, and S. Misra, "An observer-based fusion method using multicore optical shape sensors and ultrasound images for magnetically-actuated catheters," in *2018 IEEE International Conference on Robotics and Automation (ICRA)* (IEEE, 2018), pp. 50–57.

[16] P. S. Westbrook *et al.*, "Continuous multicore optical fiber grating arrays for distributed sensing applications," J. Lightwave Technol. **35**, 1248–1252 (2017).

[17] S. V. Shatalin, V. N. Treschikov, and A. J. Rogers, "Interferometric optical time-domain reflectometry for distributed optical-fiber sensing," Appl. Opt. **37**(24), 5600–5604 (1988).

[18] A. H. Hartog, O. I. Kotov, and L. B. Liokumovich, "The optics of distributed vibration sensing," paper presented at the Second EAGE Workshop on Permanent Reservoir Monitoring 2013–Current and Future Trends, 2013.

[19] G. A. Wellbrock, T. J. Xia, M.-F. Huang, Y. Chen, M. Salemi, Y.-K. Huang, P. Ji, E. Ip, and T. Wang, "First field trial of sensing vehicle speed, density, and road conditions by using fiber carrying high speed data," in *2019 Optical Fiber Communications Conference and Exhibition (OFC)* (IEEE, 2019), pp. 1–3.

[20] T. Parker, S. Shatalin, and M. Farhadiroushan, "Distributed acoustic sensing—A new tool for seismic applications," First Break **32**(2), 61–69 (2014).

[21] N. J. Lindsey, E. R. Martin, D. S. Dreger, B. Freifeld, S. Cole, S. R. James, B. L. Biondi, and J. B. Ajo-Franklin, "Fiber-optic network observations of earthquake wavefields," Geophys. Res. Lett. **44**(23), 11–792, https://doi.org/10.1002/2017gl075722 (2017).

[22] V. A. Handerek *et al.*, "Improved optical power budget in distributed acoustic sensing using enhanced scattering optical fibre," Optical Fiber Sensors, Report No. OFS-26, 2018, paper TuC5.

[23] A. Sinha, J. Lee, S. Li, and G. Barbastathis, "Lensless computational imaging through deep learning," Optica **4**(9), 1117–1125 (2017).

[24] J. Tejedor, J. Macias-Guarasa, H. F. Martins, J. Pastor-Graells, P. Corredera, and S. Martin-Lopez, "Machine learning methods for pipeline surveillance systems based on distributed acoustic sensing: A review," Appl. Sci. **7**(8), 841 (2017).

[25] A. V. Makarenko, "Deep learning algorithms for signal recognition in long perimeter monitoring distributed fiber optic sensors," in *2016 IEEE 26th International Workshop on Machine Learning for Signal Processing (MLSP), September 2016* (IEEE, 2016), pp. 1–6.

[26] M. Aktas, T. Akgun, M. U. Demircin, and D. Buyukaydin, "Deep learning based multi-threat classification for phase-OTDR fiber optic distributed acoustic sensing applications," in *Fiber Optic Sensors and Applications XIV* (International Society for Optics and Photonics, 2017), Vol. 10208, p. 102080G.