European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Time-Expansion in Distributed Optical Fibre Sensing

Miguel Gonzalez-Herraez(1), Miguel Soriano-Amat(1), Vicente Durán(2), Hugo F. Martins(3), Sonia Martin-Lopez(1), and María R. Fernández-Ruiz(1)

(1) Departamento de Electrónica, Escuela Politécnica Superior, Universidad de Alcalá, 28805 Madrid, Spain. E-mail: miguel.gonzalezh@uah.es
(2) GROC-UJI, Institute of New Imaging Technologies, University Jaume I, 12071 Castellón, Spain
(3) Instituto de Óptica “Daza de Valdés” IO-CSIC, 28006, Madrid, Spain.

Abstract *We review our work on a novel dual-comb technique to achieve a customized temporal expansion of the time-domain trace in a phase-sensitive reflectometer, that allows dynamic interrogation of strain/temperature in optical fibres with high spatial resolution (in the cm range) using only low-bandwidth photodetection (~MHz). ©2022 The Author(s)*

Introduction

Distributed optical fibre sensors based on Rayleigh backscattering are widely used in different applications, such as the monitoring of perimeters for safety purposes [1], the detection of seismic activity [2], or the monitoring of structural health in different infrastructures [3], among others. These systems can replace arrays of hundreds or thousands of point sensors, reducing the complexity and the maintenance cost of these complex systems, since the sensing and the data transmission are carried out on a single optical fibre cable. The interrogation of the fibre is typically performed either in frequency domain (OFDR) or in time domain (OTDR). These two possibilities allow us to interrogate fibres of different lengths with a different range of spatial resolutions, i.e., from tens of meters with millimetre resolution (using OFDR) [4] to >100 km with resolutions of tens of meter (using OTDR) [5,6]. In phase-sensitive (φ)OTDR, the propagation of a short, coherent probe pulse along a fibre under test (FUT) generates a backscattering signal, which provides information about each position along the fibre by time-of-flight measurements. The spatial resolution of the technique scales with the employed pulse width, being typically 1 meter per 10 ns of pulse duration. Attaining high resolutions implies, therefore, the use of short pulses and therefore high-frequency electronics in photo-detection (hundreds of MHz or GHz). Since the backscattering signal is very weak, reaching a high signal-to-noise ratio (SNR) in dynamic measurements (e.g., in Distributed Acoustic Sensing, DAS) entails the use of high energy pulses which is often not possible due to the onset of nonlinear effects. This essential limit can be partially solved by encoding the signal sent to the fibre [7,8], so longer time signals are launched into the fibre without affecting the spatial resolution. However, any time-domain technique will generally imply the use of a bandwidth adapted to the measured spatial resolution, typically from tens of MHz to a few GHz. In this paper, we present a novel high-resolution DAS that makes use of a very efficient dual frequency comb (DFC) technique to implement the interrogation process. A high-bandwidth comb (5 GHz) is used to probe the fibre with the required spatial resolution. The use of DFC technology in detection allows us to compress the bandwidth of the detected signal dramatically, thanks to an effective down-conversion of the optical signals to the electrical domain [9]. This also yields a corresponding increase in the attained signal to noise ratio. Our experimental demonstrations achieve high spatial resolution dynamic measurements (in the order of cm or below) over hundreds of meters or few kilometres fibres, using low-bandwidth photodetection and acquisition (~MHz) and an extremely simple processing (only low-pass filtering of the detected signal).

Principle of time expansion in DAS

The measurement principle and its comparison with conventional coherent detection DAS is depicted in Fig. 1 [10]. A synthesized optical frequency comb with the suitable bandwidth for the desired resolution is sent to the fibre. The comb lines are phase coded to maximize the amount of energy launched into the fibre. Upon backscattering, this comb encodes the impulse response of the fibre. The compression process is achieved by beating the backscattered signal with another comb with slightly different line spacing but the same spectral phase coding. The beating between neighbouring pairs of lines in detection leads to a spectral compression of the backscattered spectrum. Since the spectral coding of signal comb and LO comb is the same, the system directly provides the time-domain

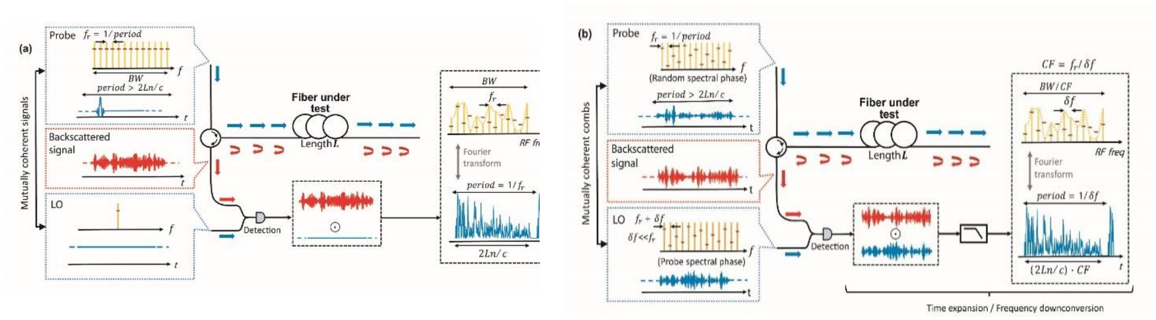

Fig. 1: (a) An example of a traditional coherent detection-based DAS scheme. A train of optical probe pulses (with a comb-like spectrum composed of in-phase lines) is launched into the fiber under test. The backscattered light is beaten with a continuous wave local oscillator (LO) and photo-detected. Both the amplitude and phase of the electromagnetic field are acquired over a bandwidth BW identical to that of the launched probe. (b) Time-expanded DAS scheme. A periodical probe signal is launched into the fiber under test. Its spectrum is a randomly phase-modulated optical comb. The backscattered light is beaten with an LO corresponding to a comb with the same number of lines and identical phase modulation as the probe comb, but with a line spacing difference δf. After photo-detection, a low pass filter passes the comb generated by the interference of the lines of the probe with the neighboring lines of the LO. Both the amplitude and phase of the electromagnetic field are acquired over a compressed bandwidth BW/CF, being CF the ratio between the probe line spacing and δf. This produces a trace temporally expanded by a factor CF. In the detection stage of both figures (central dashed boxes), the signals that are involved in the product are electromagnetic fields.

impulse response of the fibre in reflection without the need of algebraic and/or frequency-domain operations. This approach shares simultaneously the benefits of time and frequency-domain approaches, allowing to raise substantially the amount of energy reaching the detector while ensuring simple processing, low-bandwidth detection in the time domain and lower stability requirements than conventional OFDR.

Quasi-integer ratio configuration

The operation range of the proposed sensing scheme is limited due to the need of avoiding aliasing in detection. For a given optical bandwidth (set by the spatial resolution), extending the distance range implies increasing the number of probe comb lines, in order to reduce the optical spacing between them. Since the down-converted comb must lie within an RF region that extends from dc to half the optical line spacing (first Nyquist zone), generating more lines requires adjusting the frequency offset between the combs to a sufficiently low value. As the frequency offset cannot be indefinitely reduced (without dramatically slowing down the measurement process), we cannot increase the density of the comb lines at will. This fact eventually imposes a practical limitation in the length of the FUT that can be measured. However, it is possible to extend the operating range by implementing a dual frequency-comb system working in a quasi-integer-ratio mode (hereafter, QIR mode) [31]. As in the previous simple time-expansion mode, in the QIR configuration the features of the probe comb (optical bandwidth and line spacing) determine the sensing performance (spatial resolution and line spacing, respectively), while the LO comb has a similar bandwidth, but its line spacing is equal to a multiple of the probe line spacing plus a frequency offset. In the time domain picture, the operation principle of the proposed QIR configuration can be understood as a process in which a slow-repetition-rate comb is employed to interrogate the FUT, while an M times faster comb acts as LO. This second comb can be visualized as a set of slower interleaved combs, so the dual-comb system works with M time-multiplexed channels, leading to the acquisition of M offset interferograms simultaneously. Then,

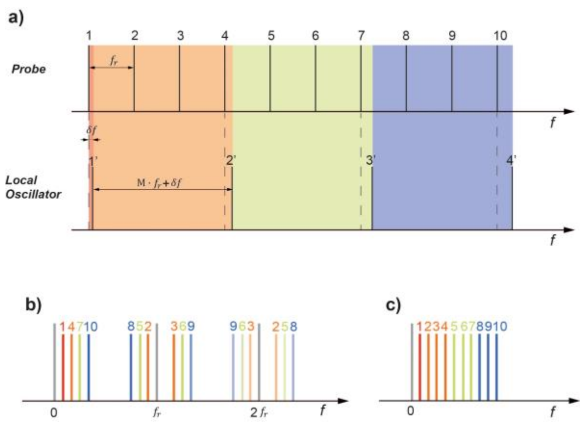

Fig. 2: Frequency domain picture of the QIR configuration. (a) The probe and the LO combs cover similar optical bandwidth but with a different number of teeth. (b) The interference of both combs generates groups of lines (Nyquist zones) on which the response of the probe is encoded. The dim lines around 2 show that there is not a unique manner of retrieving that information. (c) After rearranging the lines, a down-converted version of the probe comb can be obtained.

by demultiplexing this signal, it is possible to perform dual-comb measurements using a probe with a very small spacing without sacrificing the system speed. In the frequency domain, the interference of the backscattered comb with the LO produces a RF spectrum composed of groups of lines (Nyquist zones) located around multiples of the probe comb repetition frequency (see Fig. 2), so a down-converted version of the modulated probe can be reconstructed from the first M Nyquist zones. In that case, the condition to avoid aliasing in detection becomes also essentially relaxed by a factor M.

Example results and potential applications

Initial temperature and strain sensing experiments using the simple time expansion scheme were performed in [10]. Dynamic interrogation of fibres at 20 Hz was achieved over with a spatial resolution of 2 cm (5 GHz total probe bandwidth) and a range of 200 m (probe line spacing of 500 kHz) (see Fig 3). In this particular experiment, the detection bandwidth needs were as small as 200 kHz. The signal to noise ratio and hence the sensing performance was limited by additive noise in detection, which could be later improved in roughly 8 dB using quadratic phase coding of the probe comb [11].

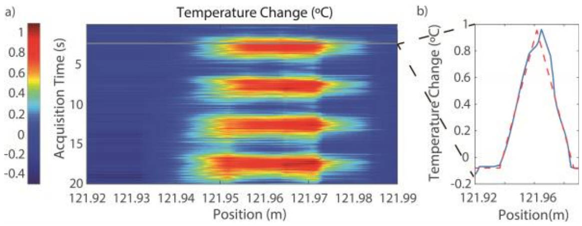

Fig. 3: Temperature sensing employing the time-expanded DAS scheme. (a) Dynamic temperature map around the perturbed area. (b) Experimentally obtained temperature profile around the maximum (blue line) and expected profile (dashed red line). The latter has been obtained by assuming a constant temperature profile along the hotspot, so the square-shaped profile of the hotspot is convolved with the 2 cm resolution window given by the gauge length. This results in a triangle shape for the measured temperature profile.

In [10], we also demonstrated the QIR configuration at relatively low M factors (50 or below). This configuration allowed us to expand the sensing range into the km range while preserving the spatial resolution in the few centimetres level and sampling frequencies in the order of tens of Hz (these improvements came at the cost of increasing the detection bandwidth by roughly a factor M, to the few MHz level). However, employing high quasi-integer ratio factors (i.e., > 100) between the probe and LO comb repetition rates was found to be challenging due to the need of sustaining good coherence among relatively long time-spaced interferograms, limiting the attainable range in this case. In a later paper [12], we formulated the frequency stability requirements of the reference clock when the QIR configuration is employed, proving its direct dependence on the number of comb lines, equivalent to the number of available independent sensing points. By using a rubidium atomic clock (relative frequency stability of ~10^{-13}), we demonstrated up to 10^5 sensing points along 1 km of fibre with tens of Hz sensing bandwidth.

Conclusions

In summary, we have explained a novel technique to induce a selectable time-domain expansion in the time domain trace of DAS systems. The technique interrogates the FUT using dual frequency comb technology with specifically tailored frequency combs. This enables to probe the fibre using a broad bandwidth optical signal, leading to high spatial resolution, but relaxing the detection and acquisition requirements extraordinarily. The probe and reference combs are spectrally phase coded using an identical code sequence. This avoids the formation of high peak power temporal pulses, spreading the launched power along the temporal period, while automatically decoding the traces at detection. Thus, it is possible to increase the energy launched to the fibre without inducing nonlinear effects, significantly increasing the SNR of the sensor. Our time-expanded approach overcomes one of the long-standing trade-offs existing in time-domain reflectometry systems, namely, the one existing between spatial resolution and detection bandwidth, allowing the achievement of centimetre resolution with MHz RF bandwidths.

Acknowledgements

We acknowledge funding from the Comunidad de Madrid and FEDER Program (P2018/NMT-4326), Generalitat Valenciana (PROMETEO/2020 /029), the Spanish Government (RTI2018–097957-B-C31, RTI2018–097957-B-C32, and RTI2018–097957-B-C33), and Universitat Jaume I (UJI-B2019–45). Also, this work has been partially funded by the Spanish Ministry of Science and Innovation MCIN/AEI/ 10.13039/ 501100011033 and by the European Union NextGenerationEU/PRTR program, under project PSI ref. PLEC2021-007875.

References

[1] G. Allwood, G. Wild and S. Hinckley, “Optical fiber sensors in physical intrusion detection systems: A review,” IEEE Sens J. 16, 5497-5509 (2016).

[2] E. F. Williams, M. R. Fernández-Ruiz, R. Magalhaes, R. Vanthillo, ZW. Zhan, M. Gonzalez-Herraez and H.F. Martins, “Distributed sensing of microseisms and teleseisms with submarine dark fibers,” Nat. Commun 10, 5778 (2019).

[3] F. Tanimola and D. Hill, “Distributed fibre sensors for pipeline protection,” J. Nat. Gas Sci. and Eng. 1, 134-143 (2009).

[4] B. J. Soller, D. K. Gifford, M. S. Wolfe, and M. E. Froggatt, "High resolution optical frequency domain reflectometry for characterization of components and assemblies," Opt. Express 13, 666-674 (2005).

[5] M. Song, W. Zhu, Q. Xia, C. Yin, Y. Lu, Y. Wu and S. Zhuang, “151-km single-end phase-sensitive optical time-domain reflectometer assisted by optical repeater,” Opt. Eng. 57, 027104 (2018).

[6] Y. Fu, Z. Wang, R Zhu, N. Xue, J. Jiang, C. Lu, B. Zhang, L. Yang, D. Atubga and Y. Rao, “Ultra-Long-Distance Hybrid BOTDA/Φ-OTDR,” Sensors 18, 976 (2018).

[7] H. F. Martins, K. Shi, B.C. Thomsen, S. Martin-Lopez, M. Gonzalez-Herraez, and S.J. Savory, “Real time dynamic strain monitoring of optical links using the backreflection of live PSK data,” Opt. Express 24, 22303-22318 (2016).

[8] D. Lee, H. Yoon, P. Kim, J. Park and N. Park, "Optimization of SNR improvement in the noncoherent OTDR based on simplex codes," J. Lightwave Technol. 24, 322-328 (2006).

[9] I. Coddington, N. Newbury, and W. Swann, “Dual-comb spectroscopy,” Optica 3, 414-426 (2016).

[10] M. Soriano-Amat, H.F. Martins, V. Durán, L. Costa, S. Martin-Lopez, M. Gonzalez-Herraez and M. R. Fernandez-Ruiz “Time-expanded phase-sensitive optical time-domain reflectometry”. Light Sci Appl. 10, 51 (2021).

[11] M. Soriano-Amat, H. F. Martins, V, Durán, S. Martin-Lopez, M. Gonzalez-Herraez, and María R. Fernández-Ruiz, "Quadratic phase coding for SNR improvement in time-expanded phase-sensitive OTDR," Opt. Lett. 46, 4406-4409 (2021)

[12] M. Soriano.Amat, H. F. Martins, V. Duran, P. Fermoso, S. Martin-Lopez, M. Gonzalez-Herraez and M. R. Fernandez-Ruiz “Frequency stability requirements in quasi-integer ratio time-expanded phase-sensitive OTDR” IEEE Journal of Lightwave Technol. (submitted)