Brillouin Optical Time-Domain Analysis: pushing back the frontiers

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ABSTRACT: These past few years the steady demand from end users has deeply stimulated the research in the field of distributed fibre sensors based on stimulated Brillouin scattering. Some recent progresses are here reported, pushing the limits beyond what has been considered as unreachable using such a system so far.

KEYWORDS: Optical fibre sensors, distributed fibre sensors, stimulated Brillouin scattering, BOTDA.

1 INTRODUCTION

Brillouin distributed fibre sensors are currently an accepted technology in the field of structure monitoring and safety and this has tremendously stimulated the demand for improved performance.

The applications are very diverse, from crack detection - requiring a centimetre spatial resolution – to pipeline survey for oil & gas industry – asking for a distance range of 100 km and more – and to dynamic monitoring of structures that needs a response time of a fraction of second.

Each of these requirements was simply considered as impossible to achieve some years ago, but all turned into reality recently. Of course they cannot all be realized simultaneously, yet, and each of them requires a specific configuration of the instrument.

These recent progresses will be reviewed hereafter, representing the future state-of-the-art of this outstanding technology that is still under steady development.

2 HIGH SPATIAL RESOLUTION

In the pioneering years of the development of Brillouin distributed fibre sensors it was commonly accepted that the spatial resolution was limited by the acoustic response time of the fibre, which sets a limit to approximately 1 metre for the spatial resolving power. An important breakthrough was realized when Hotate *et al* demonstrated that this limit can be massively reduced by using a correlation technique to localize the Brillouin interaction, instead of the classical time-resolved pulse propagation[1].

This technique demonstrated very rapidly an improvement by 2 orders of magnitude on the spatial resolution, down to the centimetre[2]. A basic limitation of the technique is a restriction on the number of resolved points that cannot exceed 500. Concretely, a spatial resolution of 1 cm is possible only over a distance range of 500 × 1 cm = 5 m. Recently by adding some complexity in the modulation scheme[3], this number of resolved points could be multiply by 3, but remains much smaller than what you can get using a standard time-domain technique.

This year an entirely different approach has been proposed to create correlations, based on a pseudo-random phase modulation that results in a single location where the 2 interacting waves keep a constant phase difference[4,5]. 9 mm spatial resolution was demonstrated over 200 m, corresponding to a very substantial increase of the number of resolved points, more than 20’000 in this case. The technique, like all correlation techniques, makes the random addressing of any point along the fibre possible, just like a Bragg grating that can be positioned and moved dynamically at any point along the fibre. This adds a big flexibility by focussing on a sensing region where an event must be monitored. Time-domain techniques only allow a sequential addressing of all points along the fibre.

If the measurement range must be extended over several kilometres, but the constraint on the spatial resolution can be slightly released, techniques based on the pre-excitation of the acoustic wave are an excellent approach[6-8]. In this case long-lasting optical waves create a background acoustic wave, which can reflect a very short pulse modulation of one of the optical wave. The duration of this pulse is so short that it does not modify significantly the acoustic wave amplitude. Different pulse formats have been proposed: a bright pulse[9], a dark pulse[10] and a π-phase pulse[11]. A careful analysis shows that the π-phase pulse gives the highest response when all other quantities are kept constant[11].

The very small but existent change of the acoustic wave amplitude due to the short pulse generates a ghost signal that can screen the real response. For this reason a measurement procedure has been proposed, based on the differential comparison of 2 traces acquired with and without pulse modulation, that cancels the impact of the ghost signal[11,12]. So far this technique has been tested with various spatial resolutions over different distance range: 2 cm resolution over 2 km[13], 5 cm resolution over 5 km[11] and 50 cm resolution over 50 km[14]. Coincidentally or not, all these results correspond to 100’000 resolved points.

3 EXTENDED DISTANCE RANGE

Using a standard configuration a distance range of 50 km can be routinely realized with a metre spatial resolution. However many installations in energy distribution and oil & gas industry span over much longer distances and there is currently a strong demand for ranges of 100 km or more, with a spatial resolution below 5 m. Extending the range from 50 km to 100 km is not simply improving the system response by a factor 2, since the main limitation on the sensing distance results from the fibre attenuation that causes an exponential decay of the signal power. Concretely, the signal power is reduced by a factor 10 over an additional 50 km.

The situation is even worse in a distributed fibre sensor, since the response must return to the fibre input and will experience again the same attenuation. So eventually this additional 50 km will result in a reduction of the detected response by a factor 100! The challenge is identical to improving the spatial resolution from 1 m to 1 cm.

Since the power of the interacting signals cannot be raised indefinitely as a result of nonlinear effects[15] and depletion[16,17], smart strategies have to be implemented to extend the range. Among the most promising the following techniques can be cited: pulse sequence coding to improve the signal-to-noise ratio[18-20], distributed Raman amplification[21-23] or even both combined together[24,25]. The record performance is currently 120 km with a 1 m spatial resolution[25].

Extending the range turns out to be extremely challenging, somehow more than improving the spatial resolution. Without a significant technological breakthrough it is not expected that a distance much larger than 120 km can be reached in a near future.

4 FAST DYNAMIC MEASUREMENTS

If the acquisition of a temporal trace can be realized in a matter of milliseconds, the fact that a frequency scan is required to reconstruct the distribution of the Brillouin gain spectrum along the fibre turns out to be very time consuming. A reasonable distribution can only be obtained in a time ranging from seconds to minutes, depending on the required accuracy.

To accelerate the acquisition, different strategies have been proposed, mainly to circumvent the frequency scan. One simple approach is to convert the frequency shift difference into a gain (or amplitude) difference, by positioning the probe frequency on the edge of the gain spectral distribution, where the slope is maximum[26]. A single trace needs to be acquired and a 200 Hz acquisition frequency has been reported, fully compatible with distributed dynamic measurements in many large structures.

As described this technique only works over a limited range of strain/temperature and if the static distribution of strain/temperature is very uniform along the fibre, so that the distribution of the Brillouin gain spectrum is identical at all positions. To circumvent this latter issue a solution has been proposed based on a frequency-agile optical probe signal[27] that is configured to match the maximum slope condition at all positions, even in presence of strong non-uniformity.

This latter concept has been further improved to also circumvent the first issue – the limited strain/temperature range – using another format to build the frequency-agile probe signal, by sequentially addressing in the same temporal trace all frequencies needed to reconstruct the distributed Brillouin gain spectrum[28]. A full distributed strain/temperature measurement at a frequency rate > 800 Hz could be obtained over a 100 m fibre with a 1.3 m spatial resolution.

4 CONCLUSIONS

Some impressive recent progresses on distributed Brillouin optical fibre sensors have been reported, demonstrating a vivid research activity in which new concepts are constantly proposed. This consolidates the position of such sensors as a future powerful tool for the monitoring and the safety of our natural and constructed environment.

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REFERENCES:

[1] Hotate, K., "Measurement of Brillouin gain spectrum distribution along an optical fiber using a correlation-based technique-proposal, experiment and simulation", *IEICE Transactions on Electronics* E83-C(3), 405-411 (2000)

[2] Hotate, K. and Tanaka, M., "Distributed fiber Brillouin strain sensing with 1-cm spatial resolution by correlation-based continuous-wave technique", *IEEE Photonics Technology Letters* 14(2), 179-181 (2002)

[3] Mizuno, Y., He, Z. and Hotate, K., "Measurement range enlargement in Brillouin optical correlation-domain reflectometry based on temporal gating scheme", *Opt. Express* 17(11), 9040-9046 (2009)

[4] Zadok, A., Antman, Y., Primerov, N., Denisov, A., Sancho, J. and Thevenaz, L., "Random-access distributed fiber sensing", *Laser & Photonics Reviews* 6(5), L1-L5 (2012)

[5] Primerov, N., Antman, Y., Sancho, J., Zadok, A. and Thevenaz, L., "Brillouin distributed sensing using localized and stationary dynamic gratings", *Photonics Europe*, Proc. SPIE 8439, 843908 (2012)

[6] Bao, X., Brown, A., DeMerchant, M. and Smith, J., "Characterization of the Brillouin-loss spectrum of single-mode fibers by use of very short (<10-ns) pulses", *Opt. Lett.* 24(8), 510-512 (1999)

[7] Lecœuche, V., Webb, D. J., Pannell, C. N. and Jackson, D. A., "25 km Brillouin based single-ended distributed fibre sensor for threshold detection of temperature or strain", *Optics Communications* 168(1-4), 95-102 (1999)

[8] Beugnot, J.-C., Tur, M., Foaleng Mafang, S. and Thévenaz, L., "Distributed Brillouin sensing with sub-meter spatial resolution: modeling and processing", *Opt. Express* 19(8), 7381-7397 (2011)

[9] Zou, L., Bao, X., Wan, Y. and Chen, L., "Coherent probe-pump-based Brillouin sensor for centimeter-crack detection", *Opt. Lett.* 30(4), 370-372 (2005)

[10] Brown, A. W., Colpitts, B. G. and Brown, K., "Dark-Pulse Brillouin Optical Time-Domain Sensor With 20-mm Spatial Resolution", *J. Lightwave Technol.* 25(1), 381-386 (2007)

[11] Foaleng, S. M., Tur, M., Beugnot, J. C. and Thevenaz, L., "High Spatial and Spectral Resolution Long-Range Sensing Using Brillouin Echoes", *Journal of Lightwave Technology* 28(20), 2993-3003 (2010)

[12] Li, W., Bao, X., Li, Y. and Chen, L., "Differential pulse-width pair BOTDA for high spatial resolution sensing", *Opt. Express* 16(26), 21616-21625 (2008)

[13] Dong, Y., Zhang, H., Chen, L. and Bao, X., "2 cm spatial-resolution and 2 km range Brillouin optical fiber sensor using a transient differential pulse pair", *Appl. Opt.* 51(9), 1229-1235 (2012)

[14] Liang, H., Li, W., Linze, N., Chen, L. and Bao, X., "High-resolution DPP-BOTDA over 50 km LEAF using return-to-zero coded pulses", *Opt. Lett.* 35(10), 1503-1505 (2010)

[15] Foaleng, S. M. and Thevenaz, L., "Impact of Raman scattering and modulation instability on the performances of Brillouin sensors", *21st International Conference on Optical Fiber Sensors*, 7753, 77539V (2011)

[16] Thevenaz, L., Foaleng Mafang, S. and Lin, J., "Impact of pump depletion on the determination of the Brillouin gain frequency in distributed fiber sensors", *21st International Conference on Optical Fiber Sensors*, 7753, 775322 (2011)

[17] Thevenaz, L., Foaleng Mafang, S. and Lin, J., "Depletion in a distributed Brillouin fiber sensor: practical limitation and strategy to avoid it", *21st International Conference on Optical Fiber Sensors*, 7753, 7753A7755 (2011)

[18] Soto, M. A., Bolognini, G., Di Pasquale, F. and Thévenaz, L., "Simplex-coded BOTDA fiber sensor with 1 m spatial resolution over a 50 km range", *Opt. Lett.* 35(2), 259-261 (2010)

[19] Soto, M. A., Taki, M., Bolognini, G. and Di Pasquale, F., "Optimization of a DPP-BOTDA sensor with 25 cm spatial resolution over 60 km standard single-mode fiber using Simplex codes and optical pre-amplification", *Opt. Express* 20(7), 6860-6869 (2012)

[20] Soto, M. A., Bolognini, G. and Pasquale, F. D., "Long-range simplex-coded BOTDA sensor over 120km distance employing optical preamplification", *Opt. Lett.* 36(2), 232-234 (2011)

[21] Rodriguez-Barrios, F., Martin-Lopez, S., Carrasco-Sanz, A., Corredera, P., Ania-Castanon, J. D., Thevenaz, L. and Gonzalez-Herraez, M., "Distributed Brillouin Fiber Sensor Assisted by First-Order Raman Amplification", *Lightwave Technology, Journal of* 28(15), 2162-2172 (2010)

[22] Angulo-Vinuesa, X., Martin-Lopez, S., Nuno, J., Corredera, P., Ania-Castanon, J. D., Thevenaz, L. and Gonzalez-Herraez, M., "Hot spot detection over 100 km with 2 meter resolution in a Raman-assisted Brillouin distributed sensor", *21st International Conference on Optical Fiber Sensors*, 7753, 775309 (2011)

[23] Soto, M. A., Bolognini, G. and Di Pasquale, F., "Optimization of long-range BOTDA sensors with high resolution using first-order bi-directional Raman amplification", *Opt. Express* 19(5), 4444-4457 (2011)

[24] Jia, X.-H., Rao, Y.-J., Deng, K., Yang, Z.-X., Chang, L., Zhang, C. and Ran, Z.-L., "Experimental Demonstration on 2.5-m Spatial Resolution and 1°C Temperature Uncertainty Over Long-Distance BOTDA With Combined Raman Amplification and Optical Pulse Coding", *IEEE Photonics Technology Letters* 23(7), 435-437 (2011)

[25] Soto, M. A., Taki, M., Bolognini, G. and Di Pasquale, F., "Simplex-Coded BOTDA Sensor Over 120 km SMF with 1 m Spatial Resolution Assisted by Optimized Bidirectional Raman Amplification", *IEEE Photonics Technology Letters* 24(99), in press doi:10.1109/lpt.2012.2212183 (2012)

[26] Bernini, R., Minardo, A. and Zeni, L., "Dynamic strain measurement in optical fibers by stimulated Brillouin scattering", *Opt. Lett.* 34(17), 2613-2615 (2009)

[27] Peled, Y., Motil, A., Yaron, L. and Tur, M., "Slope-assisted fast distributed sensing in optical fibers with arbitrary Brillouin profile", *Opt. Express* 19(21), 19845-19854 (2011)

[28] Peled, Y., Motil, A. and Tur, M., "Fast Brillouin optical time domain analysis for dynamic sensing", *Opt. Express* 20(8), 8584-8591 (2012)