

# High Spatial and Spectral Resolution Long-Range Sensing Using Brillouin Echoes

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**Abstract:** While classical configurations have a practical spatial resolution of 1 meter, novel approaches have been demonstrated that can overcome this limit to offer spatial resolutions in the centimetre range, while preserving full measurand accuracy.

**OCIS codes:** (060.2370) Fiber optics sensors; (290.5900) Scattering, stimulated Brillouin.

Optical fibre sensors based on stimulated Brillouin scattering have now clearly demonstrated their excellent capability for long-range distributed strain and temperature measurements. The fibre is used as sensing element and a value for temperature and/or strain can be obtained from any point along the fibre. While classical configurations have practically a spatial resolution limited by the phonon lifetime to 1 meter, novel approaches have been demonstrated these past years that can overcome this limit. This can be achieved either by the prior activation of the acoustic wave by a long lasting pre-pumping signal, leading to the optimized configuration using Brillouin echoes, or by probing a classically generated steady acoustic wave using a ultra-short pulse propagating in the orthogonal polarization of a highly birefringent fibre. These novel configurations can offer spatial resolutions in the centimetre range, while preserving the full accuracy on the determination of temperature and strain.

The commonly accepted opinion that the spatial resolution of a pulse-based Brillouin sensor is limited to 1 m was seriously questioned when Bao *et al* observed an unexpected narrowing of the Brillouin gain spectrum down to its natural linewidth when pulses turned shorter than the phonon lifetime (6 ns) [1]. It is now unanimously accepted by all specialists that this special behaviour results from a pre-excitation of the acoustic wave through the presence of a continuous background pump [2]. Basically, the observation of this effect depends on the pre-existence of an important acoustic wave in the fibre medium vibrating at the exact Brillouin frequency resonance. This acoustic wave is conveniently generated through stimulated Brillouin scattering using a continuous wave at the probe frequency and another continuous wave (or a long pulse) at the pump frequency. Among the 3 waves involved in the interaction, the 2 optical waves can experience very fast changes in their amplitude and phase, while the acoustic wave presents a highly inertial behaviour and requires a typical time equal to a multiple of its 6 ns lifetime to adapt to a new situation. For instance, if the pump is suddenly turned off, the acoustic wave will gradually decay and will still exist during the typical duration of its lifetime, despite the absence of stimulated interaction.

This inertial property is used to change very briefly amplitude or phase of the pump, during a time  $T$  so short that the acoustic wave does not experience a notable change ( $T \ll$  phonon lifetime). This way the pump will be reflected by the acoustic wave, but under transient conditions that do not correspond to those required by amplitude and phase matching. This will cause an abrupt change of the steady state amplification of the probe that can be observed by a fast detection scheme. The pre-existence of the acoustic wave is essential and, since it is stimulated by continuous optical waves, a response will be observed only over the natural local Brillouin gain spectrum along the fibre. To highlight the similarity with spin echoes, this new concept is named *Brillouin echo* because it turns out to be formally very similar to the description of the interaction of nuclear spins with magnetic fields in nuclear magnetic resonance.

The Brillouin echo can be observed essentially with 3 different pump pulse coding: bright pulse, dark pulse and  $\pi$ -phase pulse. This latter coding turns out to give the best contrast under equivalent pump power conditions [3, 4]. Figure 1 (left) shows the distribution of Brillouin amplification over the last 40 m of a 4.57 km fibre, obtained using a 500 ps  $\pi$ -phase pulse [5]. A 5 cm segment showing a distinct Brillouin shift can be clearly identified and measured even after several kilometres of fibre, as shown in the right graph of Figure . Recently the range could be even extended to 10km, reaching the tremendous record of 200'000 independently resolved points. The accuracy on the Brillouin shift determination remains comparable to a standard BOTDA technique, since no significant broadening of the measured Brillouin spectrum is observed.

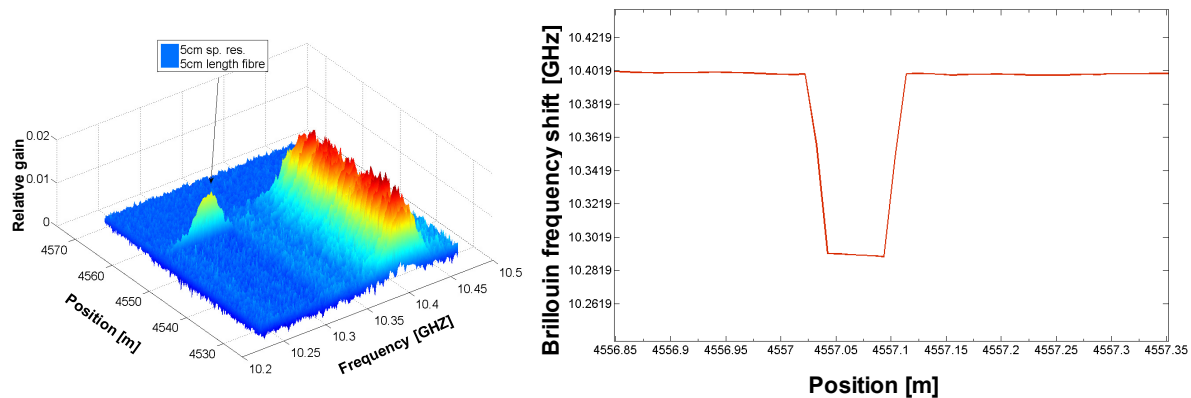


Figure 1. Left: 3D view of the signal amplification obtained using the BEDS technique in a differential configuration with 500 ps  $\pi$ -phase shifts on the pump. Here are shown the 40 last meters of a 4.57 km fibre, where a 5 cm segment showing a distinct Brillouin shift is inserted. Right: distribution of the Brillouin frequency shift at the position of this segment obtained after processing, showing that the segment is clearly resolved (horizontal axis limited to a 1.5 m range).

As an extension of the principle of Brillouin echoes, the concept of Brillouin dynamic grating (BDG) has been newly implemented in polarization-maintaining fibres (PMF) [6-8], where acoustic waves generated during the process of stimulated Brillouin scattering (SBS) by optical waves (pump waves) in one polarization are used to reflect an orthogonally-polarized wave (probe wave) at a different optical frequency from the pump. BDG can also be applied to enhance the spatial resolution of an ordinary Brillouin optical time-domain analysis (BOTDA) system by replacing the Brillouin probe with the reflection from the BDG. It is possible this way to acquire a narrowband Brillouin gain spectrum (BGS) with a broadband pulse using the BDG, and measurements with a 0.5 cm spatial resolution have been demonstrated experimentally, which is the best result ever reported using a time-domain Brillouin sensor [9, 10].

This shows the huge progresses achieved these past few years in Brillouin time-distributed sensing, showing the possibility to resolve events with a spatial resolution in the centimetre range. This is fully comparable to point sensors such as fibre Bragg gratings, however showing the great flexibility of a fully continuous distributed sensing, equivalent to many thousands of distinct point sensors and requiring no special fibre preparation. This will certainly cause a significant change in the appreciation of this type of sensors, by broadening the field of applications to small and medium-size structures.

- [1] X. Bao, A. Brown, M. DeMerchant, and J. Smith, "Characterization of the Brillouin-loss spectrum of single-mode fibers by use of very short (<10-ns) pulses," *Opt. Lett.* 24, 510-512 (1999).
- [2] V. Lecoecueche, D. J. Webb, C. N. Pannell, and D. A. Jackson, "Transient response in high-resolution Brillouin-based distributed sensing using probe pulses shorter than the acoustic relaxation time," *Opt. Lett.* 25, 156-158 (2000).
- [3] J.-C. Beugnot, M. Tur, S. Foaleng Mafang, and L. Thévenaz, "Distributed Brillouin sensing with sub-meter spatial resolution: modeling and processing," *Opt. Express* 19, 7381-7397 (2011).
- [4] L. Thevenaz and S. F. Mafang, "Distributed fiber sensing using Brillouin echoes," in 19th International Conference on Optical Fibre Sensors, (SPIE, 2008), 70043N.
- [5] S. M. Foaleng, M. Tur, J. C. Beugnot, and L. Thevenaz, "High Spatial and Spectral Resolution Long-Range Sensing Using Brillouin Echoes," *Journal of Lightwave Technology* 28, 2993-3003 (2010).
- [6] K. Y. Song, W. Zou, Z. He, and K. Hotate, "All-optical dynamic grating generation based on Brillouin scattering in polarization-maintaining fiber," *Opt. Lett.* 33, 926-928 (2008).
- [7] Y. Dong, X. Bao, and L. Chen, "Distributed temperature sensing based on birefringence effect on transient Brillouin grating in a polarization-maintaining photonic crystal fiber," *Opt. Lett.* 34, 2590-2592 (2009).
- [8] K. Y. Song, W. Zou, Z. He, and K. Hotate, "Optical time-domain measurement of Brillouin dynamic grating spectrum in a polarization-maintaining fiber," *Opt. Lett.* 34, 1381-1383 (2009).
- [9] K.-Y. Song, S. Chin, N. Primerov, and L. Thevenaz, "Time-domain distributed sensor with 1 cm spatial resolution based on Brillouin dynamic gratings," in 20th International Conference on Optical Fibre Sensors, (SPIE, 2009), 75037V-75034.
- [10] S. Chin, N. Primerov, and L. Thevenaz, "Sub-centimetre Spatial Resolution in Distributed Fibre Sensing, based on Dynamic Brillouin Grating in Optical Fibers," *IEEE Sensors Journal*, PP, 1-1 (2011) <http://dx.doi.org/10.1109/JSEN.2011.2126568>.