MG4 (Invited)
9:30 AM – 10:00 AM

# Dynamic Brillouin Gratings: a New Tool in Fibers for All-Optical Signal Processing

**Luc Thévenaz, Nikolay Primerov, Sanghoon Chin, Marco Santagiustina***
*EPFL Swiss Federal Institute of Technology, Institute of Electrical Engineering, STI-GR-SCI-LT,*
*Station 11, 1015 Lausanne, Switzerland*
**CNIT-Department of Information Engineering, University of Padova, via Gradenigo 6b, 35131, Padova, Italy*
*Author e-mail address: Luc.Thevenaz@EPFL.CH*

**Abstract:** The recent possibility to generate dynamic Bragg gratings by the interaction of 2 optical waves through stimulated Brillouin scattering in highly birefringent fibers has opened a new field to realize all-optical fiber-based functions.

**OCIS codes:** (060.4370) Nonlinear optics, fibers; (290.5900) Scattering, stimulated Brillouin; (070.4340) Nonlinear optical signal processing

The generation of dynamic Bragg gratings by the interaction of 2 optical waves through stimulated Brillouin scattering has offered the possibility to implement all-optical functions that were so far impossible to realize in optical fibers. Using this feature a local and temporary grating can be placed at any position along an optical fiber and can be repositioned dynamically with a total flexibility through a purely optical interaction. This new tool has found direct applications in all-optical delay lines, demonstrating a tunable delaying capacity of more than 1 microsecond with an ideal reconfiguration time. But it turns out that its field of application is much vaster, from optical storage and analog operations on the signal (time reversal, derivative, integration) to distributed sensing with an extreme spatial resolution.

## I. Principle

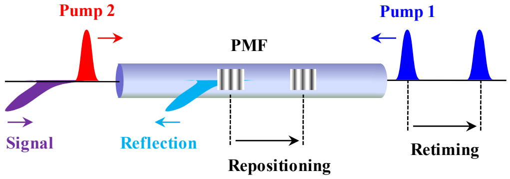

Fig. 1. Principle to generate a dynamic Brillouin grating (DBG) in a polarization maintaining fiber, based on the ordinary process of stimulated Brillouin scattering, and to realize a localized movable reflection of an orthogonally polarized signal wave.

The generation of dynamic Brillouin gratings is based on the following principle [1]: two intense optical waves counterpropagating along the slow axis of a polarization maintaining fiber can create a localized acoustic grating (Brillouin dynamic grating) at a given point using SBS if they are properly modulated (e.g. optical pulses), as shown in Fig.1. Since the created Brillouin dynamic grating is longitudinal, it can reflect a signal pulse with polarization along the orthogonal axis if the frequency of the signal satisfies the Bragg condition imposed by the grating. In a PM fiber refractive indices are different for the two orthogonal states of polarization, leading for a given physical pitch of the Brillouin dynamic grating to different optical pitches for slow and fast axes. This leads to a shift of the grating resonance for the fast axis to another optical frequency. This way it is possible to reflect a signal pulse polarized along the fast axis with the grating created by optical waves along the slow axis and to entirely decorrelate the processes of grating dynamic generation and signal reflection. The frequency difference between the resonances for the two orthogonal axes is fixed by the local birefringence of the fiber.

## II. All optical tunable delay line

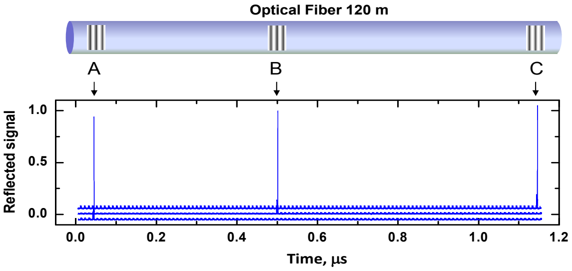

Fig. 2. Reflected pulses on dynamic Brillouin gratings positioned at 3 successive positions (A,B,C) along a 120m HiBi fiber. 650 ps pulses could be delayed by more than 1 µs with minor distortion.

Since reflecting gratings are created at any position along the fiber, a signal pulse can be also reflected at different points, thus showing a delay due to the time-of-flight for the back-reflected signals [2].

Since the acoustic grating can only be built up where the SBS interaction between the two pump pulses takes place, it can be flexibly created at any preset position over the entire length of the HiBi fiber, simply by retiming Pump 1 pulse. Using this principle an isolated signal pulses with FWHM duration of 650 ps was continuously delayed up to 1.15 µs through a 120 m long PMF, equivalent to a fractional delay of 1769. This system is also suitable for a real data bit sequence, but with a maximum delay limited by the temporal decay of the acoustic wave. Solutions are actively sought to override this limit through a smart coding of the waves generating the grating.

## III. Analog signal processing

The acoustic grating generated by the modulated pumps turns out to have a spatial distribution given by the convolution between the 2 pumps. Different operations can be realized using this property and the result can be read using the reflected signal. For instance an optical signal can be stored and retrieved at a later time when one of the pump is the signal to be stored and a very short pulse is used for the other pump. This way the generated acoustic wave is an exact spatial replica of the signal to be stored and the material vibration remains static in the fiber. It can be read at a later time using a very short orthogonally polarized reading pulse reflected on this acoustic wave. If this reading pulse is launched from the opposite end of the fiber, a time-reversed copy of the input signal is retrieved [3], as shown in Fig.3.

By convolving the input signal modulating one of the pump with a variety of different temporal waveform for the other pump, other operations have been demonstrated, such as optical integration and differentiation [4].

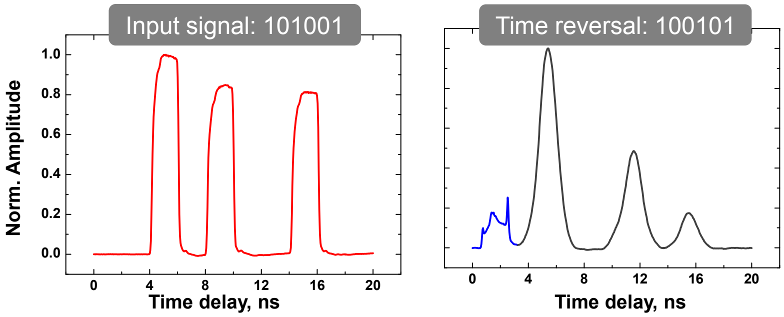

Fig. 3. Time reversed copy of a data sequence obtained by storing the signal in a static acoustic vibration in the fiber and retrieved using a signal launched in the opposite direction. The decaying amplitude of the retrieved signal is due to the finite acoustic damping time in the silica (typ. 10ns).

## IV. Distributed sensing

When the 2 intense counterpropagating waves generating the grating are continuous, the acoustic wave extends all over the fiber length and its local amplitude is proportional to the local Brillouin gain in the fiber. By reflecting a very short pulse in the orthogonal polarization, a map of the local amplitude of the acoustic wave can be obtained in the time domain. By incrementally varying the frequency difference between the 2 intense counterpropagating waves and recording for each step the local amplitude of the acoustic wave, the local spectral distribution of the Brillouin can be retrieved and the local value of the Brillouin shift can be calculated [5]. It is well-known that the Brillouin shift is very dependent on the temperature and the strain experienced by the fiber. A spatial resolution of 6 mm could be demonstrated using this system, as illustrated in Fig.4. 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.

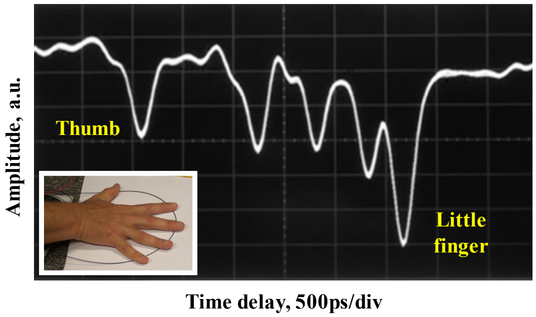

Fig. 4. Temporal distribution of the signal pulse reflection along the sensing fiber when 5 fingers from one hand are placed on the fiber, as shown in the inset image. The pump frequency difference is adjusted to give a maximal reflection at ambient temperature. The local heating of the fingers is sufficient to create enough detuning which results in a localized drop of the Brillouin grating reflectivity exactly at the fingers position.

## References

[1] K. Y. Song, W. Zou, Z. He, and K. Hotate, Opt. Lett. **33**, 926-928 (2008).

[2] N. Primerov, S. Chin, K. Y. Song, and L. Thevenaz, in *Optical Fiber Communication Conference*, OSA Technical Digest OWF6, (2010).

[3] S. Chin, N. Primerov, K. Y. Song, L. Thevenaz, M. Santagiustina, and L. Ursini, in *Nonlinear Photonics (NP)*, OSA Technical Digest NThA6, (2010).

[4] N. Primerov, S. Chin, L. Thévenaz, L. Ursini, and M. Santagiustina, in *Slow and Fast Light*, OSA Technical SLMA3, (2011).

[5] K. Y. Song, S. Chin, N. Primerov, and L. Thevenaz, Journal of Lightwave Technology **28**, 2062-2067 (2010).