Differential chirped-pulse pair for sub-meter spatial resolution Brillouin distributed fiber sensing

Sébastien Le Floch*[a], Zhisheng Yang[b,c], Florian Sauser[a], Marcelo A. Soto[b], Luc Thévenaz[b]
[a] HE-ARC, Rue de la Serre 7, CH-2610 Saint Imier, Switzerland;
[b] EPFL, Swiss Federal Institute of Technology, Institute of Electrical Engineering, SCI-STI-LT Station 11, CH-1015 Lausanne, Switzerland;
[c] Permanent address: State Key Laboratory of Information Photonics & Optical Communications,Beijing University of Posts and Telecommunications, Beijing 100876, China.
*sebastien.lefloch@he-arc.ch; phone +41 32 930 22 49; fax +41 32 930 22 04; www.he-arc.ch

ABSTRACT

A distributed fiber sensor based on a differential chirped-pulse pair Brillouin optical time domain analysis (DCP-BOTDA) is proposed for sub-meter spatial resolution sensing. The technique is based on the subtraction of two measurements made with the same pump pulse widths, but differing in the final short section of the pulse by a positive or negative frequency chirp, respectively. Experimental results are compared with a precise theoretical modeling, validating the sub-meter sensing capabilities of the technique.

Keywords: Stimulated Brillouin scattering, fiber-optics sensors, distributed fiber sensors.

1. INTRODUCTION

Distributed optical fiber sensors using stimulated Brillouin scattering (SBS) are widely used for structural health monitoring, especially for strain and/or temperature sensing. The standard technique, called Brillouin optical time-domain analysis (BOTDA), is based on a pump-probe interaction, in which the spatial resolution is given by the pump pulse duration[1]. Since the temperature or strain information is contained in the frequency domain (Brillouin frequency), the accuracy of these sensors is inversely related to the pump pulse duration and the material response time, practically limiting the spatial resolution down to 1 meter[2]. In the past ten years, several configurations have been proposed to achieve sub-meter spatial resolution, one of them being the differential pulse-width pair BOTDA (DPP-BOTDA): the method consists of two measurements with different pulse-widths, while the local information is retrieved by subtracting both measurements in the time-domain[3]. This technique is actually a smart simplification of a formerly known technique including a short π-phase shift at the end of the second pulse[4], thus creating a destructive interference between the optical waves and resulting in a signal-to-noise ratio larger by 3dB with respect to the DPP-BOTDA. Recently, the Brillouin phase subtraction of the DPP method was implemented using a coherent detection scheme[5].

In this paper, we propose another approach to break the symmetry between two long pulses of equivalent lengths, by abruptly and briefly shifting the frequency of the pump pulses. A complete theoretical model validates the technique and supports the results obtained over a 1.5 km-long fiber, where two stressed sections of 30 cm are resolved.

2. THEORETICAL DESCRIPTION OF THE DCP-BOTDA SENSOR

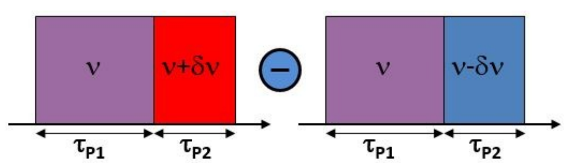

Figure 1: chirped pulses configuration for DCP-BOTDA

The principle of the differential chirped-pulse pair BOTDA (DCP-BOTDA) method proposed in this paper is presented in Fig. 1: each chirped pump pulse has a first long section (at a constant frequency ν), which pre-activates the acoustic wave. Then the symmetry is broken by introducing an abrupt positive (negative) frequency change (± δν) in the second

24th International Conference on Optical Fibre Sensors, edited by Hypolito José Kalinowski, José Luís Fabris, Wojtek J. Bock, Proc. of SPIE Vol. 9634, 96341D · © 2015 SPIE
CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2194705

section of the first (second) pulse. Sub-meter spatial resolution is obtained after subtraction of the frequency-scanned time-domain traces. The optimization of the method clearly depends on the time duration of the two pulse sections and on the frequency chirp that is applied to the second section of the pulses. In order to fully describe the temporal evolution of the acoustic wave and probe signal, the corresponding SBS coupled equations are solved:

$$\left(\frac{\partial}{\partial z}+\frac{1}{v_g}\frac{\partial}{\partial t}\right)E_P = i\frac{1}{2}g_2 Q E_S \quad (1) \qquad \left(-\frac{\partial}{\partial z}+\frac{1}{v_g}\frac{\partial}{\partial t}\right)E_S = i\frac{1}{2}g_2 Q^* E_P \quad (2) \qquad \left(\frac{\partial}{\partial t}+\Gamma_A\right)Q = i g_1 E_P E_S^* \quad (3)$$

where E_P, E_S and Q are slowly-varying envelopes of the pump, probe and acoustic fields; $g_{1,2}$ are the electrostriction and elasto-optic coefficients; $\Gamma_A = i2\pi\nu + \pi\Delta\nu_B$ is the frequency detuning and damping parameter, $\Delta\nu_B$ is the Brillouin linewidth and ν the frequency detuning between the local Brillouin frequency shift (BFS) and the frequency difference between the pump and the probe waves. The chirped pump pulse can be represented as:

$$E_P(t) = E_P^0\left\{u(t)-u(t-\tau_{P1})+\exp[\mp i2\pi\delta\nu(t-\tau_{P1})]u(t-\tau_{P1})-\exp[\mp i2\pi\delta\nu(t-\tau_{P1})]u(t-\tau_{P1}-\tau_{P2})\right\} \quad (4)$$

where $\delta\nu$ is the frequency chirp on the final part of the pump pulse, and u(•) is the Heaviside step function. By solving Eq. (1-4), the Brillouin gain contribution on probe wave of a short fiber section of length Δz is:

$$\begin{aligned}\Delta E_S(\Delta z,t) = {} & \frac{g\Delta z I_P^0 E_S^0}{2\Gamma_A^*}\left\{[1-e^{-\Gamma_A^* t}][u(t)-u(t-\tau_{P1})]+\left[e^{-\Gamma_A^*(t-\tau_{P1})}-e^{-\Gamma_A^* t}\right]e^{\mp i\Delta\omega(t-\tau_{P1})}[u(t-\tau_{P1})-u(t-\tau_{P1}-\tau_{P2})]\right\} \\ & +\frac{g\Delta z I_P^0 E_S^0}{2(\Gamma_A^*\pm i\Delta\omega)}\left\{\left[1-e^{-(\Gamma_A^*\pm i\Delta\omega)(t-\tau_{P1})}\right]e^{\mp i\Delta\omega(t-\tau_{P1})}[u(t-\tau_{P1})-u(t-\tau_{P1}-\tau_{P2})]\right\}\end{aligned} \quad (5)$$

Summing up Eq. (5) over all positions covered by the pulse, the Brillouin gain observed in the time trace at a given position z can be obtained. An optimized configuration for τ_{P2} =4 ns (corresponding to a potential 40 cm spatial resolution) is achieved for the following parameters: τ_{P1} =20 ns and $\delta\nu$=100 MHz.

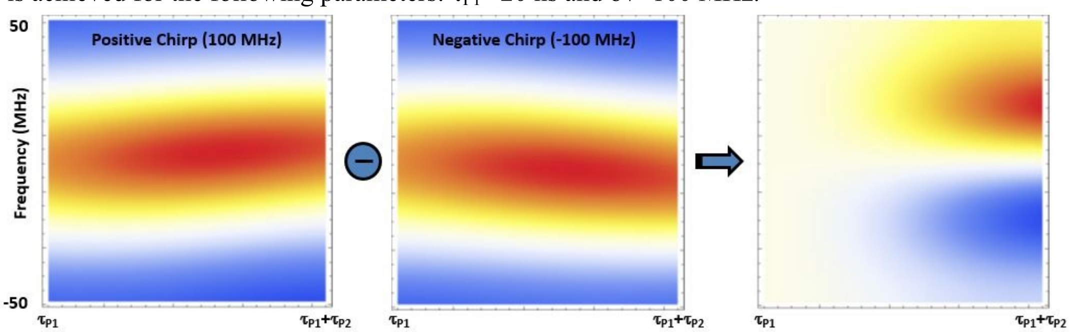

Figure 2: Simulation of the temporal evolution of the probe amplitude during the second section of the pulses in the DCP-BOTDA method; left: positive chirp; center: negative chirp; right: result after subtraction of both responses.

Fig. 2 shows the response on the probe wave at a given fiber location during the final section of the pump pulses, for a frequency scan $\Delta\nu$ from -50 MHz to 50 MHz around the Brillouin peak frequency. The positive (negative) chirp drags the probe response to raise (decrease) its frequency, thus leading after subtraction to a distinct frequency response. The Brillouin frequency is simply given the crossing by zero amplitude obtained after subtraction. The observed frequency difference between both extrema is about 40 MHz. Fig. 3 shows the spectrum of the probe signal after subtraction as a function of the frequency detuning for different pump parameters (chirp and pre-activation time) and for τ_{P2} =4 ns. Within all these conditions, the optimized value for the chirp parameter to maximize the amplitude contrast of the subtraction has been found to be between 80 MHz and 100 MHz and the pre-activation time duration should be $\tau_{P1} \geq 16$ ns. The frequency difference between the two extrema (minimum and maximum of the subtraction) tends to the natural Brillouin linewidth $\Delta\nu_B$. Contrary to the π-phase shift technique, where the probe experiences an abrupt destructive interference - equivalent to a loss process - during the second section of the pulse, the DCP-BOTDA gradually shifts the interferometric phase. Following the Rayleigh ¼ wave criterion, the interference is constructive as long as the phase shift does not exceed π/2, which means that the maximum frequency chirp is given by the relation $2\pi\delta\nu\tau_{P2} = \pi/2$. Hence, for τ_{P2} =4 ns, the acoustic wave will keep its strength for a frequency chirp $\delta\nu$=60 MHz, which is slightly inferior to what our model suggests. The reason of this can be explained as follows: with a positive chirped pump pulse $\delta\nu$=100 MHz, a destructive interference process occurs on the probe wave at frequencies where a constructive interference occurs for the respective negative chirped pump pulse. After subtracting the two probe waves, the amplitude contrast turns out to be slightly higher, even if the strength of the single measured probe is not maximum.

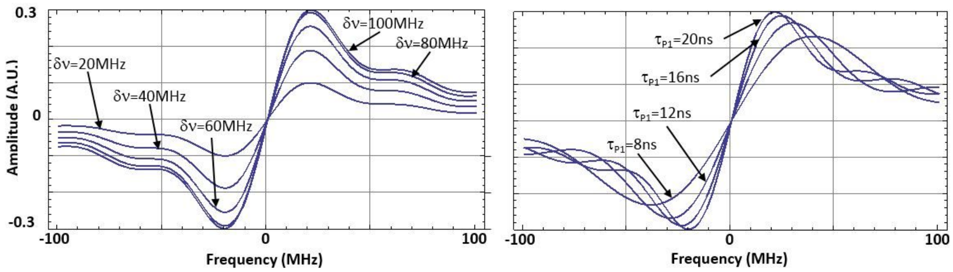

Figure 3: probe signal obtained after subtraction (τ_{P2}=4ns); left: influence of the chirp parameter; right: influence of the first section time duration for a fixed chirp parameter (δν=100MHz).

3. EXPERIMENTAL DEMONSTRATION

In order to experimentally validate the DCP-BOTDA method proposed in this paper, measurements have been carried out along a 1.5 km-long standard single-mode fiber. The experimental set-up is based on the generation of chirped pump pulses using an arbitrary waveform generator (AWG) that drives an intensity modulator operating in suppressed carrier mode[6]. The AWG is able to deliver a new frequency every 4 ns, with neither glitch nor phase hop. The rise and fall times of the pump pulses are well below 1 ns, which is an essential condition for differential techniques. The bandwidth of the detector is 350 MHz (matching the expected spatial resolution), and each temporal trace is averaged 1000 times. The sampling rate of the acquisition card is set to 1Gs/s, corresponding to a measurement point every 10 cm. Fig. 4 (left) shows the two Brillouin gain spectra (BGS) obtained with DCP-BOTDA at the end of the fiber. A good agreement is observed between the theoretical model (solid lines) and data (circles), even if a slight asymmetry can be observed, probably due to power fluctuations of the chirped pump pulses. It is interesting to point out that each BGS has an apparent linewidth matching that of an equivalent (τ_{P1}+τ_{P2}/2) null-chirped pump pulse duration. Fig. 4 (right) shows the subtraction of the two BGS, confirming the presence of slow oscillations in the frequency domain, as predicted by the model.

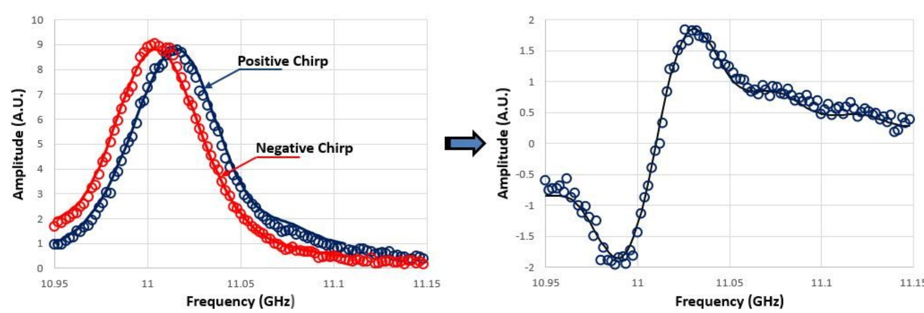

Figure 4: left: BGS at 1.4 km; right: subtraction of BGS. Empty circles: measurements; solid lines: theoretical model.

Fig. 5 shows the DCP measurement at the end of the sensing fiber, where two fiber sections of 30 cm are stressed and separated by a 30 cm loose fiber. Both sections, under an applied strain of about 0.1%, are resolved, which is eventually better than the theoretical spatial resolution of 40 cm, the system benefiting from a dead zone during transients (see Fig.2).

Finally, we have compared the Brillouin frequency shifts (BFS) measured by DCP-BOTDA with a DPP-BOTDA using a 24/20 ns pulse pair (Fig. 6). The BFS has been obtained by a quadratic fitting around both extrema, although other methods such as a linear fitting may be used for the proposed DCP method. The BFS profiles in both cases are in very good agreement. It has been experimentally verified that the measurement contrast using the DCP-BOTDA is two-fold the contrast obtained with the conventional DPP-BOTDA. This can be easily explained by the push-pull configuration of the DCP-BOTDA that doubles the effect of the response on the probe wave.

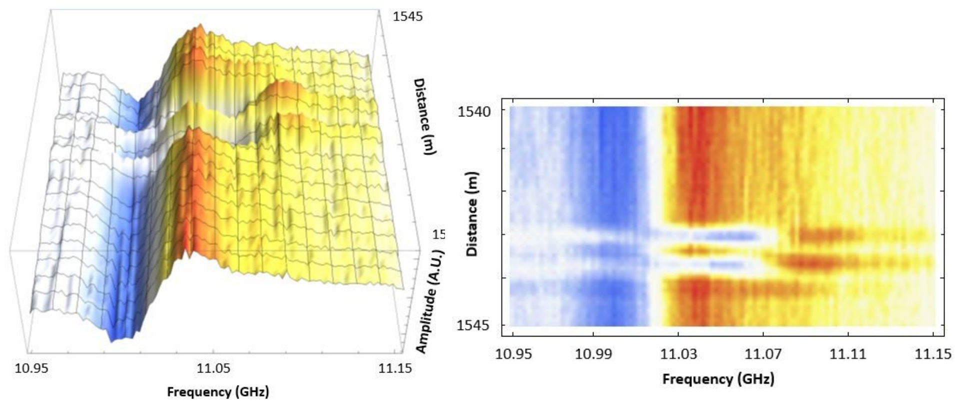

Figure 5: 3D plot (left) and top-view plot (right) of the measured BGS subtraction at 1.54km fiber, where the fiber is stressed.

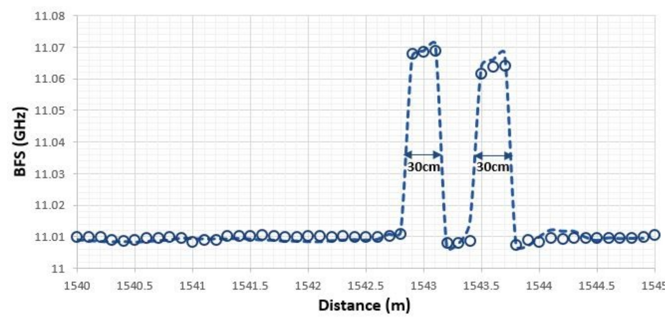

Figure 6: BFS at the end of the sensing fiber, where two sections are stressed (30cm each with a 30cm loose fiber in the middle). Empty circles: DCP-BOTDA; dashed line: DPP-BOTDA.

4. CONCLUSION

A novel distributed fiber sensor for sub-meter spatial resolution is proposed based on frequency shift keying within the pump pulse. Measurements are validated experimentally and theoretically through an analytical solution calculated from the SBS coupled equations. A comparison with the DPP-BOTDA shows that the signal-to-noise ratio (SNR) is doubled thanks to the intrinsic push-pull effect given by the method. The scheme requires no modification of the experimental set-up used for coding, so that both techniques may be easily combined, thus increasing the SNR for fast measurements.

The authors acknowledge the support from the Swiss Commission for Technology and Innovation (Project 13122.1) and Z. Yang is thankful to the China Scholarship Council for supporting his stay at EPFL

REFERENCES

[1] Horiguchi, T., Kurashima, T. and Tateda, M., "A technique to measure distributed strain in optical fibers", *IEEE Photonics Technology Letters* 2(5), 352-354 (1990)

[2] Fellay, A., Thévenaz, L., Facchini, M., Niklès, M. and Robert, P., "Distributed sensing using stimulated Brillouin scattering : towards ultimate resolution", *12th Int. Conference on Optical Fiber Sensors*, 16, OWD3 (1997)

[3] 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)

[4] 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)

[5] Urricelqui, J., Sagues, M. and Loayssa, A., "Phasorial differential pulse-width pair technique for long-range Brillouin optical time-domain analysis sensors", *Optics Express* 22(14), 17403-17408 (2014)

[6] Le Floch, S., Sauser, F., Soto, M. A. and Thévenaz, L., "Time/frequency coding for Brillouin distributed sensors", *OFS2012 22nd International Conference on Optical Fiber Sensors*, Proc. SPIE 8421, 84211J (2012)