Optimized shaping of isolated pulses in Brillouin fiber slow-light systems

Sanghoon Chin* **and Luc Thévenaz**

Ecole Polytechnique Fédérale de Lausanne, STI-GR-SCI Station 11, CH-1015 Lausanne, Switzerland
**Corresponding author: sanghoon.chin@epfl.ch*

Received December 16, 2008; revised January 19, 2009; accepted January 20, 2009;
posted February 5, 2009 (Doc. ID 105280); published March 2, 2009

The effect of a proper shaping of the temporal envelope of isolated pulses in slow-light systems based on stimulated Brillouin scattering in optical fibers is studied and experimentally demonstrated. The pulse shape can be optimized to lead to a substantial enhancement of the delaying effect. The spectrum of the optical pulses is engineered so that the spectral width of the pulse is minimized while preserving the pulse duration, making possible to match at best the Brillouin spectrum. Exponentially shaped pulses show the minimal FWHM spectral width and experience the largest time delay when compared to Gaussian or rectangular pulses. © 2009 Optical Society of America

OCIS codes: 060.2310, 290.5900, 060.4370, 350.5500.

Over the past decade, slow- and fast-light devices have attracted considerable interest, since they have probed one of the key challenges to realize all-optically tunable delay lines for photonic signal processing. Several experiments are successfully demonstrated, showing a wide control of the group velocity of a light pulse from delays exceeding pulse duration to superluminal propagation or even negative group velocity [1].

However, slow-light systems based on stimulated Brillouin scattering (SBS) [2,3] have proved to date to be an unmatched and an unprecedented flexible tool as a result of their unique spectral tailoring capability. Toward the objective of a real implementation, solutions were proposed to enlarge the bandwidth of the Brillouin resonance [4–6] and to optimize its dispersion characteristics [7–9]. All these experiments modified the Brillouin spectrum by slightly modulating the current applied to the pump laser so that the effective gain spectrum is broadened to contain the entire pulse spectrum. Although such SBS slow-light systems appear to be very promising timing tools, they clearly need a set of optimizations to get the maximum benefit for a given bandwidth, since a broader resonance results in a lower delaying efficiency that can be compensated only at the expense of a higher pump power.

Here we investigate an optimization based on the time-domain intensity profile of a pulse signal to modify its spectrum for a best fit within the Brillouin gain bandwidth. We place our study in the context of a delay line used for tunable timing purposes and not for the transmission of information through a continuous data stream. In our particular case it is assumed that a train of isolated pulses is transmitted to carry the timing information that is extracted when the pulse amplitude crosses a preset level, typically 50% of its peak amplitude. Clearly the scope of this paper is definitely more oriented to metrology applications than the telecommunication domain. Since the overlap between adjacent pulses is noinexistent, issues related to intersymbol interferences can be ignored, and the relevant quantities to characterize the pulse for this class of applications will be the position of its peak—or front edge—and its FWHM temporal and spectral widths. This approach is therefore distinct from a recent complete study [10] in which the pulse shape is optimized for a continuous data stream for communication applications. In this latter case relevant quantities characterizing the pulse are different, and in particular rms temporal and spectral widths have to be considered. This leads to optimal pulse shapes that are substantially different in the two studies.

The relationship between a pulse shape and its optical spectrum can be characterized by its time-bandwidth product K. This parameter is essentially given by the product of Δv and Δt, here defined as the FWHM of the spectral and temporal distributions, respectively. Table 1 shows the values of K for various pulse shapes in the case of transform-limited pulses [11]. It turns out that, for a given pulse duration, its spectral width can be substantially modified by properly shaping the pulse envelope. Thereby a significant narrowing of the effective spectral width in terms of the FWHM can be obtained. The pulses can therefore be spectrally well confined in the center of the Brillouin resonance, where a perfect linear transition in the effective refractive index is observed. As a result, we could achieve larger delays of the pulse peak or front edge.

In a simulation test, we defined three different pulse intensity profiles with an identical FWHM duration, showing successively exponential, Gaussian, and rectangular temporal distributions. The spectra of the pulses were numerically obtained through a

Table 1. Values of the FWHM Time-Bandwidth Product *K* for Various Pulse Shapes[a]

Shape	$\epsilon(t)$	K
Gaussian function	$\exp[-(t/t_0)^2/2]$	0.441
Exponential function	$\exp[-(t/t_0)/2]$	0.140
Rectangular function	$u(t+t_0/2)-u(t-t_0/2)$	0.892
Lorentzian function	$[1+(t/t_0)^2]^{-1}$	0.142

[a] $u(t)$ is the unit step function at the origin.

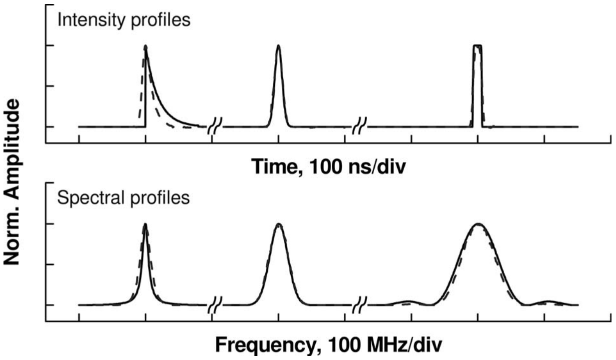

Fig. 1. Studied pulses (exponential, Gaussian, and rectangular time distribution from left to right with corresponding spectra on bottom chart). Numerical and measured results are shown in solid and dashed curves, respectively.

Fourier transform of the pulse waveforms as shown in Fig. 1. It is clearly observed that as anticipated the different pulses show different spectral widths. Then, to demonstrate the validity of the proposed approach, we experimentally generated the three different pulse shapes with an identical 14 ns FWHM duration by using an arbitrary waveform generator. The spectral widths of the differently shaped pulses were measured by the typical delayed self-homodyne method based on a Mach–Zehnder interferometer in which one arm contains a delay line to break the coherence of the analyzed beat signal. The measured pulse spectra show a good agreement with the numerical predictions, clearly illustrating the spectral width dependence on the pulse time-domain waveform. Unavoidable small deviations remain in the spectral width, which are induced by the smoothed rising and falling edges of the pulses. Among these intensity profiles, the exponential pulse offers the narrowest FWHM spectral width of 18 MHz, while the Gaussian and rectangular pulses show a measured spectral width of 35 and 58 MHz, respectively.

Figure 2 depicts the schematic of the experimental setup. As a Brillouin gain medium a 1-km-long standard single-mode fiber was used. The Brillouin characteristics of this fiber were measured, showing a Brillouin shift of 10.8 GHz and an SBS gain bandwidth of 27 MHz. The experimental validation has been realized using the natural Brillouin gain without engineered broadening, since the bandwidth issues are less critical for timing applications and the gain spectral characteristics are fully stable and accurately known. However, the approach can be extrapolated to any gain spectral distribution, in particular when the spectrum is synthetically broadened.

A commercial distributed-feedback laser diode (DFB-LD) operating at 1532 nm was used as a light source, and its output was modulated through an electro-optic Mach–Zehnder intensity modulator at half the Brillouin frequency shift to generate two first-order sidebands. The dc bias on the modulator was well set so that the carrier was completely suppressed and only two sidebands are present at the output. Each sideband was then filtered and directed to a distinct fiber using a set of two fiber Bragg gratings associated with two circulators. The higher frequency sideband was amplified using an erbium-doped fiber amplifier (EDFA) to play the role of the Brillouin pump, and its power was precisely controlled by a variable optical attenuator. The lower frequency sideband was launched into another external modulator to properly shape the pulse signal so that trains of signal pulses with distinct intensity profiles are generated showing an identical 14 ns FWHM pulse duration.

To observe the delaying effect induced by the Brillouin gain, the pump power was varied from 0 to 50 mW. The temporally delayed pulses after propagation through the fiber were measured as a function of the pump power using a fast detector and displayed on a digital oscilloscope. Figure 3 shows the normalized time waveforms of the signal pulses with a different pulse envelope for a set of fixed pump levels: 0, 20, 35, and 50 mW. In all situations the pulses experience more delay for an increasing pump power, as expected from an SBS slow-light system, but it is clearly observed that the exponentially shaped pulse achieves the largest delay. When rectangular and Gaussian pulses exit the fiber, significant distortion is imposed onto the signal pulses and

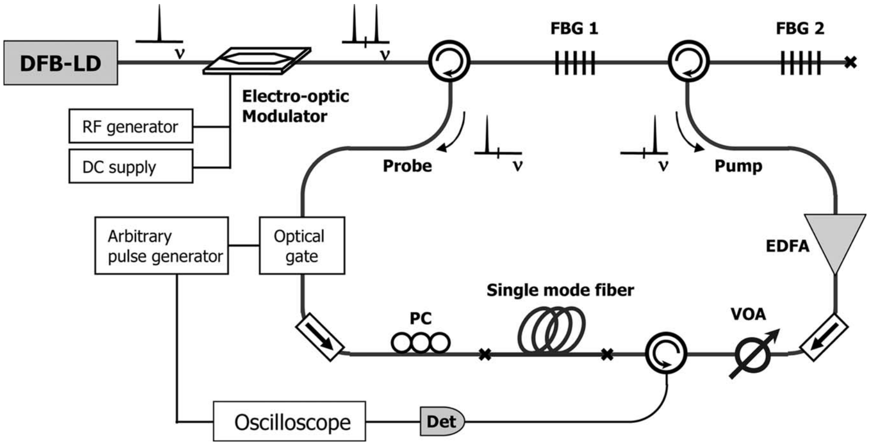

Fig. 2. Experimental setup to demonstrate the impact of the pulse shape on the time delay through Brillouin slow light. FBG, fiber Bragg grating; EDFA, erbium-doped fiber amplifier; VOA, variable optical attenuator; PC, polarization controller; DFB-LD, distributed-feedback laser diode.

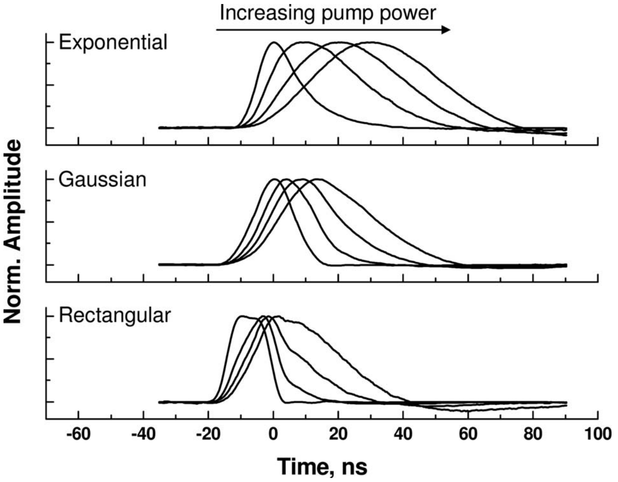

Fig. 3. Normalized time traces of the signal pulses with pump powers at 0, 20, 35, and 50 mW, showing a clear time-delay dependence on the pulse shape.

a reduced time delay is observed, since these two pulses suffer by essence a stronger spectral filtering effect by the narrower Brillouin resonance.

In previous works [2–5], temporal delays induced by SBS were evaluated in terms of Brillouin gain. However, in this experiment the pulse delays are rather plotted as a function of the pump power for a flat comparison between the time delays obtained in the three different cases, as shown in Fig. 4, with the effective gain value being substantially different for different pulse shapes. To evaluate the amount of time delay, we determined the peak position of the signal pulse. It is interesting to immediately point out that, for a given pump power and fixed input pulse duration, the obtained time delay is larger with a reduced distortion when the pulse shaping results in a smaller FWHM spectral width. However, the pulse delaying remains unavoidably accompanied by a pulse broadening as a result of the spectral filtering (low-pass filter) in the slow-light process. The largest time delay achieved by the exponential pulse is about 31 ns (or a fractional delay of 2.1) with a broadening factor of 3. For comparison we calculated that in a typical SBS slow-light system an equivalent delay for 14 ns FWHM Gaussian pulses would result in a broadening factor of 3.4. The advantage may look minor in terms of broadening, but the main benefit of the optimized pulse shape turns out to be the following: the signal delay shows a linear dependence on the pump power with a slope efficiency of 0.73 ns/nW for the exponential pulse. In the Gaussian case, this slope efficiency is observed to be 0.28 ns/mW, resulting in a 2.5 times decrease when compared to the exponential pulse.

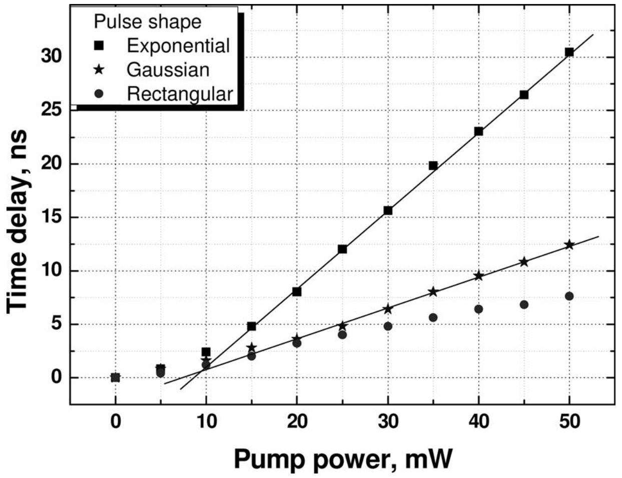

Fig. 4. Temporal delays of the signal pulses as a function of the pump power.

In conclusion, we have demonstrated a novel approach to enhance the time delay of SBS slow-light systems for isolated pulses through an intelligent shaping of the pulse envelope to optimize the pulse spectral extension. This approach has the advantage to minimize the FWHM spectral width for a best matching to the bandwidth of a given Brillouin gain resonance. The spectral filtering effect causing a significant signal distortion can be reduced to a large extent. In this optical delaying scheme, a tunable delay of up to 31 ns equivalent to 2.1 pulse widths was obtained in the case of exponentially shaped pulses in a single delaying stage. The efficiency of the delaying process can thus be improved using that optimized profile by a factor 2.5 compared to a Gaussian pulse. It should be mentioned that this description is justified when the FWHM widths of the time and the spectral distributions are considered, the product of the rms time and spectral widths keeping of course minimized for Gaussian pulses. This approach is justified for timing applications when a transition threshold is defined to determine the pulse arrival time. It must also be pointed out that the exponential pulse also offers another spectral optimization in the sense that its spectral distribution is Lorentzian as the natural Brillouin gain spectrum. This also indicates that a particular pulse shape is certainly optimal for a given gain spectral shape.

This work was supported by the Swiss National Science Foundation (SNSF) through project 200021-109773.

References

1. R. W. Boyd and D. J. Gauthier, *in Progress in Optics*, E. Wolf, ed. (Elsevier, 2002), Chap. 6, p. 497.
2. K. Y. Song, M. G. Herráez, and L. Thévenaz, Opt. Express **13**, 82 (2005).
3. Y. Okawachi, M. S. Bigelow, J. E. Sharping, Z. Zhu, A. Schweinsberg, D. J. Gauthier, R. W. Boyd, and A. L. Gaeta, Phys. Rev. Lett. **94**, 153902 (2005).
4. M. G. Herráez, K. Y. Song, and L. Thévenaz, Opt. Express **14**, 1395 (2005).
5. Z. Zhu, A. M. C. Dawes, D. J. Gauthier, L. Zhang, and A. E. Willner, J. Lightwave Technol. **25**, 201 (2007).
6. K. Y. Song and K. Hotate, Opt. Lett. **32**, 217 (2007).
7. A. Zadok, O. Raz, A. Eyal, and M. Tur, IEEE Photon. Technol. Lett. **19**, 462 (2007).
8. R. Pant, M. D. Stenner, M. A. Neifeld, and D. J. Gauthier, Opt. Express **16**, 2764 (2008).
9. M. Lee, R. Pant, and M. A. Neifeld, Appl. Opt. **47**, 6404 (2008).
10. M. D. Stenner and M. A. Neifeld, Opt. Express **16**, 651 (2008).
11. C. Rulliere, *Femtosecond Laser Pulses* (Springer-Verlag, 1998).