Zero-gain slow & fast light propagation in an optical fiber

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Abstract: Slow & fast light with null amplification or loss of a light signal is experimentally demonstrated. This novel method for producing zero-gain slow & fast light takes advantage of the great flexibility of stimulated Brillouin scattering in optical fibers to generate synthesized gain spectra. Generation of optical delays and advancements with minor amplitude change is realized through the superposition of gain and loss profiles showing very different spectral widths, resulting in a synthesized spectral profile identical to an ideal electromagnetically-induced transparency.

OCIS codes: (060.2310) Fiber optics; (290.5900) Scattering, stimulated Brillouin; (060.4370) Nonlinear optics, fibers; (350.5500) Propagation

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1. Introduction

Slow & fast light is known to be a very attractive approach to achieve all-optical delay lines and to provide a timing tool for photonics signal processing. A significant step towards real applications has been achieved last year when slow light was experimentally and efficiently

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demonstrated in optical fibres using stimulated Brillouin scattering (SBS) [1,2]. Extremely wide group velocity control in the fiber was readily achieved using SBS and group velocities as small as 71000 km/s, superluminal and even negative group velocities were observed for the first time in optical fibers [3]. Slow light was soon also successfully achieved in optical fibers using other nonlinear interactions [4,5] with larger natural bandwidth but much reduced efficiency.

Actually stimulated Brillouin scattering has proved to be an unprecedented and unmatched flexible tool for the generation of slow light regarding its spectral tailoring capability. Indeed, a wide variety of gain spectral profile can be obtained by properly modulating the pump spectrum. For instance fast light in gain regime was achieved using a two-tone pump spectrum, resulting in overlapping gain profiles and eventually a reversed linear phase variation [6]. More recently it was demonstrated that the bandwidth of SBS-based slow light can be made arbitrarily large by actively broadening the pump spectrum using random direct current modulation of the pump laser [7], to ultimately reach a 10 GHz bandwidth [8]. All these techniques suffer from the drawback of a significant amplitude change associated with the delaying effect, which may be highly impairing in a real system. Indeed, the delaying effect in slow & fast light is intimately related to a narrowband gain or loss process. So one-pulse width delaying gives rise to a large 30dB pulse amplitude change with typical SBS characteristics in silica optical fibers [1,3].

This problem was soon identified like severe in the early experiments on slow & fast light using atomic absorptions, the high loss rendering the output pulse unobservable for large delays. Elegant solutions were proposed to open transparency windows in narrow atomic absorption lines, such as coherent population oscillation [9] and electromagnetically-induced transparency [10], this latter demonstrating large delay with much reduced amplitude change.

We demonstrate here that the high flexibility of SBS offers the possibility to synthesize a gain spectral profile, so that a signal delay or advance is achieved with an absolute null amplitude change. This can be obtained by the combination of gain and loss spectral profiles with identical depth but different width, resulting in a net zero gain and a differential delaying effect. The possibility to finely tune independently the depth of each spectral profile results in a perfect compensation of gain and loss, like an ideal electromagnetically-induced transparency spectral profile. The scheme can be applied indifferently to generate slow or fast light and this is to our knowledge the first time that continuously tunable optical delays with zero amplitude change are experimentally achieved using slow & fast light.

2. Principle

Slow & fast light is observed when a sharp spectral change in the medium transmission results in a steep linear variation of the effective refractive index in the frequency domain. This in turn results in a strong group velocity change at the exact center of the resonance. A signal propagating in a medium showing a linear gain G will experience a net amplitude change by a factor $\exp(G)$, together with an extra delay T, due to the associated group velocity change. For a gain or loss process following a Lorentzian spectral distribution such as SBS, linear gain G and delay T are simply given by [1-3,11]:

$$G = g_o I_p L_{eff} \qquad \text{and} \qquad T = \frac{G}{2\pi\Delta\nu} \tag{1}$$

where $\Delta\nu$ is the half width at half maximum of the Lorentzian distribution, g_o is the peak value of the Brillouin gain, L_{eff} is the effective length of fiber and I_p is the intensity of the pump.

The delay T thus depends on two parameters: the linear gain G (negative sign for loss) and the bandwidth $\Delta\nu$ of the gain or loss process. It was formerly demonstrated [1-3] that a gain can be generated using SBS by placing a pump frequency at a frequency $+\nu_B$ above the signal frequency, ν_B being the Brillouin shift. On the contrary, an equivalent loss can be generated as well simply by placing the pump frequency at a frequency $-\nu_B$ below the signal frequency that will generate a negative delay, hence pulse advancement or “fast light” [1,3].

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Now let superpose in the frequency domain a SBS gain with linear gain $+G_1$ and a bandwidth $\Delta\nu_1$ on a SBS loss with negative linear gain (thus loss) $-G_2$ and a bandwidth $\Delta\nu_2$, as shown in Figure 1. They are generated using 2 distinct pump lasers placed at a frequency $\pm\nu_B$ above and below the signal frequency ν, respectively. The bandwidth of each pump $\Delta\nu$ can be arbitrarily broadened and controlled using the scheme proposed in [7,8].

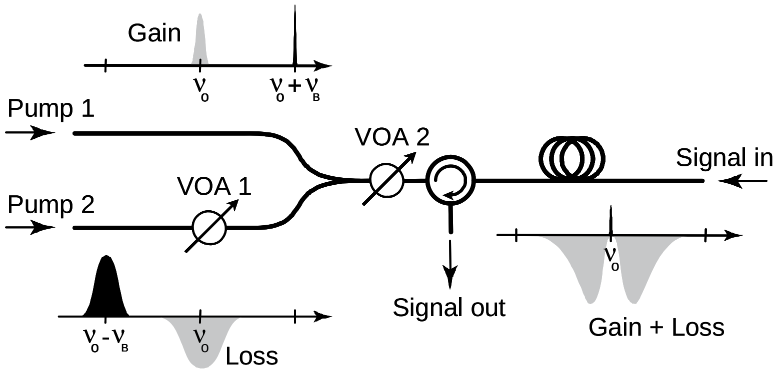

Fig.1. Principle of the experimental configuration to generate zero-gain spectral resonances where two distinct optical pumps were used to produce Brillouin gain and loss, respectively.

The resulting linear gain G_{net} and the overall delay T_{net} are therefore:

$$G_{net} = G_1 - G_2 \qquad \text{and} \qquad T_{net} = \frac{G_1}{2\pi\Delta\nu_1} - \frac{G_2}{2\pi\Delta\nu_2} \tag{2}$$

If $G_1=G_2$, then:

$$G_{net} = 0 \qquad \text{and} \qquad T_{net} = \frac{G_{1,2}}{2\pi}\left(\frac{1}{\Delta\nu_1} - \frac{1}{\Delta\nu_2}\right) \tag{3}$$

If the bandwidths of the gain and loss spectra are substantially different, e.g. $\Delta\nu_2 \gg \Delta\nu_1$, it is possible to obtain a significant time delay T_{net} with nevertheless a zero linear gain G_{net}. The effect is fully comparable to electromagnetically-induced transparency or coherent population oscillation, in which a transparency window is opened in the middle of an absorption line. The configuration offers a large flexibility, since a spectral hole can be similarly created in a gain line by swapping the spectral positions of the broad and narrow pumps, to generate fast light. In addition the supplementary degree of freedom offered by the possibility to tune the pumps spectral width makes possible to control to a wide extent the slope between time delay T_{net} and the pump powers.

3. Experimental configuration

Figure 2 shows a schematic diagram of the experimental set-up used to demonstrate the zero-gain delays. A conventional step-index 2 km optical fiber was used as SBS gain/loss medium. Pump 1 was kept unmodulated and spectrally placed at a frequency $\nu+\nu_B$ above the pulsed probe signal at ν, so that the frequency difference between Pump 1 and signal is equal to the Brillouin frequency shift ν_B. This way it generated a narrowband SBS gain showing a bandwidth $\Delta\nu_1$ given by the natural Brillouin bandwidth of 20-30 MHz in silica optical fibers

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in the low loss transmission window. To secure a high stability of the frequency difference between Pump 1 and signal, these two optical waves were generated through modulation of the CW light from one commercial DFB laser diode emitting at a wavelength of 1532 nm. This is achieved by modulating the laser light using an electro-optic Mach-Zehnder intensity modulator at half the Brillouin frequency shift – i.e. 5.4 GHz – using a CW microwave generator. The DC bias voltage on the modulator is set, so that a full extinction of the carrier is achieved and the optical spectrum at the modulator output contains only the two modulation sidebands, exactly separated by the Brillouin frequency shift of 10.8 GHz [1,3,6]. Each sideband is then filtered and directed in distinct fibers using a set of 2 fiber Bragg gratings associated to 2 circulators, as shown in Fig. 2. The upper sideband is then amplified by a first Erbium-doped fiber amplifier (EDFA) to a maximum power of 17dBm. The lower sideband was then modulated either sinusoidally or as a pulse train using a second electro-optic Mach-Zehnder modulator. This technique secures a total absence of spectral drift between Pump 1 and the signal, together with a perfect centering of the signal in the gain spectrum.

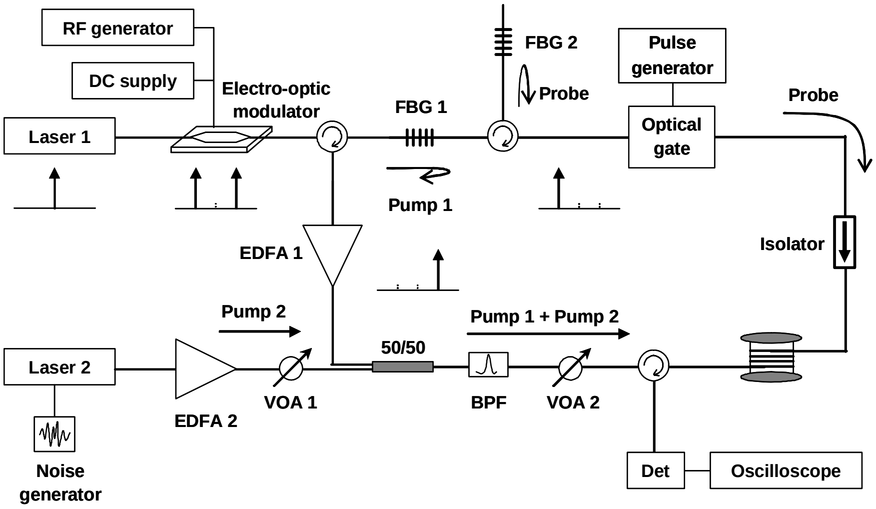

Fig.2. Experimental setup to realize zero-gain slow light via optical fibers, by spectrally superposing a gain spectrum over a loss spectrum, generated from distinct sources showing different linewidths. VOA: variable attenuator; BPF: band-pass filter; FBG: fiber Bragg grating; EDFA: Erbium-doped fiber amplifier.

Pump 2 was generated from a distinct DFB laser diode, operating at the same 1532 nm wavelength. This laser was directly modulated by superposing on the DC bias current the random signal from a noise generator, in order to substantially broaden its optical spectrum through the current-to-frequency dithering effect [7,8]. A Pump 2 linewidth $\Delta\nu_2$ up to 312 MHz could be obtained this way. The center frequency of Pump 2 was set below the signal frequency, at a frequency of $\nu-\nu_B$, so that this pump generates a broadband loss through SBS at the signal frequency ν, following the principle sketched in Fig.1.

Since the bandwidth $\Delta\nu_2$ is about 12-fold broader than the natural Brillouin linewidth $\Delta\nu_1$ induced by Pump 1 the frequency setting of Pump 2 is less critical and just requires a fine tuning by adjusting the DC bias current and temperature applied to the laser. The broadened pump was strongly boosted using a high power Er-doped fiber amplifier (~1W), since the power of Pump 2 must be larger than Pump 1 by a factor identical to the broadening factor $\Delta\nu_2/\Delta\nu_1$ to make peak gain/loss generated by the two pumps identical [7]. A first variable optical attenuator (VOA 1) was used to adjust the power of Pump 2 to make G_2 perfectly match G_1. This adjustment was carried out by substituting to the signal the light from a frequency-sweeping laser and by monitoring the signal amplitude at the fiber output. G_1 and G_2 are equal when the signal amplitude at the peak of the narrow band gain is equal to the amplitude of the signal far away from the broadband loss spectrum, as shown in Fig.3. It clearly demonstrates that the obtained spectral transmission profile of the probe after propagating through the test fiber is very similar to an ideal EIT profile. It must be pointed out that the procedure using the frequency sweeping signal is also useful to center the gain and loss spectra generated by the 2 pumps.

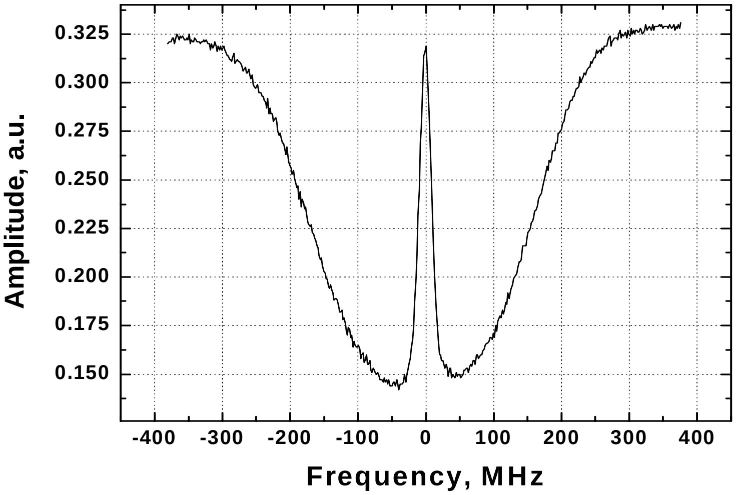

Fig.3. Variation of the amplitude of the probe signal as a function of frequency after propagation through a 2 km fiber, showing the achievement of a well-compensated SBS gain/loss profile.

It illustrates that a good compensation of gain and loss can be obtained by using two optical pumps via stimulated Brillouin scattering in optical fibers. The light from the two pumps is combined through a 3dB directional coupler and their state of polarization is aligned to get a stable and evenly distributed double SBS interaction along the fiber. The VOA 2 is then used to vary simultaneously and identically the power of the two pumps, so that the gain/loss compensation is maintained at any pumping level.

4. Results

In previous works [1-4], the temporal delay induced by the slow & fast light effect was normally measured as a function of the SBS gain/loss, as a consequence of the direct and simple relationship between these 2 quantities (see Eq. 1). But by essence this turns out to be conceptually inappropriate in our experiment since only a small residual gain/loss of the signal is observed as a result of the peak gain compensation. Hence the delays were rather evaluated as a function of the power of Pump 1, the power of Pump 2 varying proportionally. Since the gain G_1 is proportional to the Pump 1 power, a linear relation must also be observed between the induced delays and this power. It also makes comparisons possible with the standard technique by simply measuring delays using the same procedure after turning off Pump 2.

Delays and amplitudes of the probe after propagation through a 2 km standard single mode fiber were precisely measured while incrementing the Pump 1 power from 0 mW to 19 mW. The FWHM optical pulse width used in this experiment was 50 ns and typical traces

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are shown in Fig. 4. It must be pointed out that the pulses are shown with no normalization using a fixed scope vertical scale, demonstrating a moderate amplitude change due to a slight mismatch between peak gain and loss. The effect of the mismatch logically increases for higher pump levels and a perfect balance would experimentally require a dedicated feedback control circuit that was not implemented for this simple demonstration of the experimental principle. The effect of a negative mismatch was also observed as decreasing pulse amplitudes for increasing pump levels, with no noticeable effect on the observed delays. An equivalent maximum delay using the non-compensated standard technique would result in a 12 dB amplitude change using the ~1 ns/dB delay versus gain relationship commonly observed using SBS in standard single mode fibers [1].

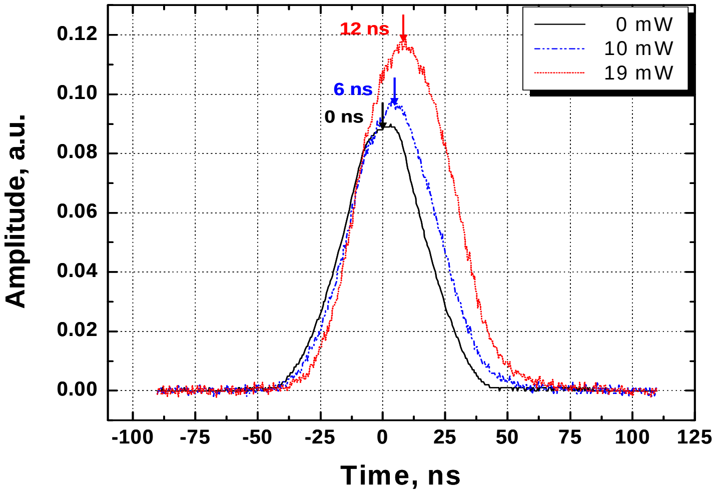

Fig.4. Time traces of the probe pulses after propagation in a fiber with a zero-gain profile for different Pump 1 powers, showing a clear delay and a minor amplitude change. Traces are non-normalized and measured in unmodified experimental conditions. Arrows indicate the pulses peak position.

To precisely determine the delays induced by the group velocity change we used a sine modulated light since the pulsed probe signals experience non-negligible distortion and pulse broadening. This way it makes possible to unambiguously obtain the real delays induced by the group velocity change without applying any arbitrary criterion, by measuring the difference between the phases of the sine modulation with and without pumping. Delays and amplitudes for a 1 MHz sine modulated signal were measured for different pump levels, as shown in Fig. 5. It clearly demonstrates that the delaying effect is maintained and fully comparable in magnitude to those obtained using the standard method [1], while observing a maximum amplitude change of 0.9 dB that can be reasonably considered as a flat response.

Actually the maximum induced delay was limited in our experiment by the onset of the amplified spontaneous Brillouin scattering generated by the spectrally broadened Pump 2. The observed threshold is well below the theoretical expectation, when taking into account the broadening effect. This is certainly due to a residual coherence in the spectral properties of Pump 2, the noise-generated broadening effect being not perfectly optimized in terms of frequency and amplitude to result in a fully chaotic linewidth enhancement. Modifications of the noise generator parameters towards optimization raised significantly the Pump 2 Brillouin threshold and this strongly supported the validity of the explanation. A full and careful optimization of the noise-generated broadening would lead to delays comparable to those

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obtained with no gain compensation.

It can also be observed in Fig 5 that the relationship between delay and pump power is not perfectly linear and deviates from the linear fit in particular for low pump levels. This effect results from the residual random birefringence in the fiber that makes the counter-propagating probe and pump waves mostly interacting with unmatched polarization. This lowers the efficiency of SBS, but it turns out that this penalizing effect is substantially reduced for high gain, since the interaction transfers photons from the pump to the probe. These coherently transferred photons keep the polarization property of the pump, so that they drag the probe polarization state towards the pump polarization, resulting in a better polarization matching. This effect is well-known by specialists familiar with SBS in optical fibers and turns out to fully dominate the residual birefringence effect for high SBS gain [12].

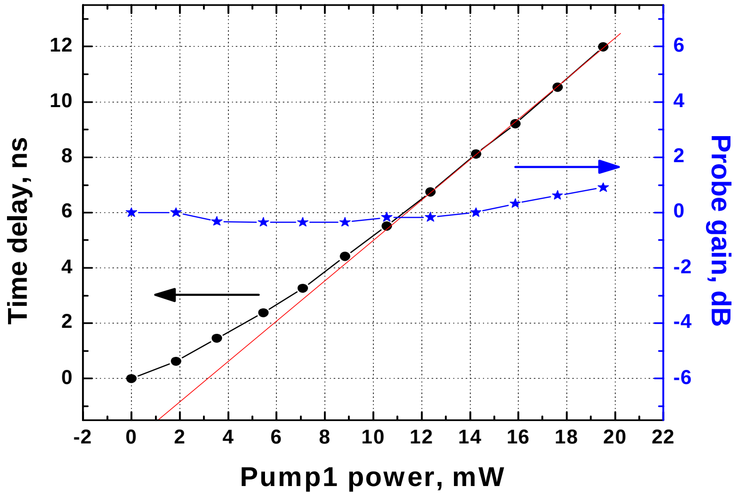

Fig.5. Delays and amplitudes for a 1 MHz sine modulated signal as a function of Pump 1 power in a zero-gain slow light configuration. Power of Pump 2 is 12 times larger than power of Pump 1.

As shown in Eq. 3 the gain compensation effect results in a decrease of the slope efficiency between gain (or Pump 1 power) and delay by a factor $(\Delta\nu_2\text{-}\Delta\nu_1)/\Delta\nu_2$ when compared to the standard technique. We could verify the validity of the model by measuring the slope efficiencies with Pump 2 turned on (gain compensation) and off (no compensation) and comparing with the expected slope reduction as calculated from the gain linewidths. The slope efficiency deduced from the linear fit was 0.709 ns/mW when Pump 2 is on and raises to 0.776 ns/mW when Pump 2 is off. Experimentally the slope is thus reduced by a factor 0.913. Using the measured broadened linewidth $\Delta\nu_2$=312 MHz, such a slope reduction would be obtained after calculation with a gain linewidth $\Delta\nu_1$=27 MHz, that is equal to the Brillouin natural gain linewidth in standard single mode fibers. This shows the perfect adequacy between the simple model and the experimental results.

The gain compensation technique can also be applied to generate fast light, by simply swapping the frequency positions of Pump 1 and Pump 2. In this case the broadened pump generates a gain and the narrow pump burns a hole at the center of the gain spectrum. This configuration was also tested and results are shown in Fig. 6. Larger Pump 1 power could be used through a smaller broadening of Pump 2 ($\Delta\nu_2$=210 MHz) that resulted in a better coherence reduction. The gain and loss compensation is nearly perfect in this case, but we observed a substantial slope efficiency reduction when compared to slow light, by nearly a factor 2 down to -0.414 ns/mW. It can only be partly explained by a smaller broadening of Pump 2 that would result in a 10% reduction of the slope efficiency.

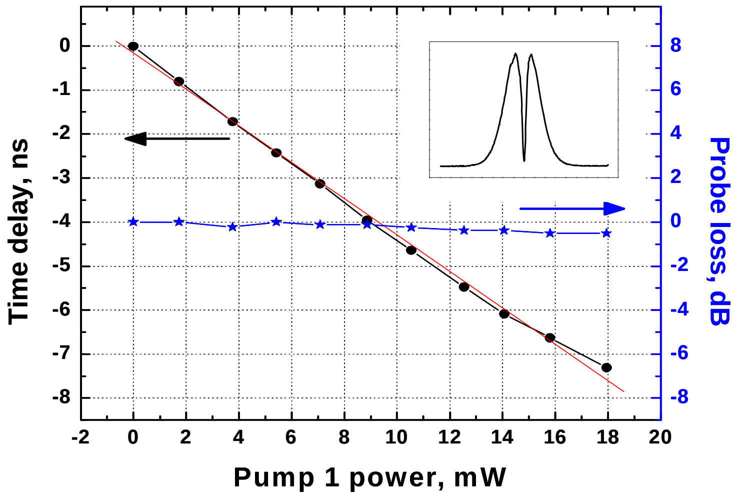

Fig.6. Advancements and amplitudes for a 1 MHz sine modulated signal as a function of pump 1 power in a zero-gain fast light configuration. Power of Pump 2 is 8 times larger than power of Pump 1. The insert shows the measured SBS gain/loss profile in this configuration.

The explanation certainly lies in the interplay between line broadening through the random frequency dithering of Pump 2 and polarization dragging effect: as a result of the frequency dithering Brillouin gain - and thus polarization dragging of the probe - occurs only at limited and random locations, so that most of the time the probe polarization is only subject to random birefringence. Matching between pump and probe polarizations is thus poorly improved even for high gain and the slope efficiency is reduced substantially, accordingly. This explains the asymmetric behavior between slow and fast light and this observation is certainly an important contribution for guiding the future design of fiber optics delay line based on spectrally-broadened SBS.

5. Conclusions

The high flexibility of stimulated Brillouin scattering to produce slow & fast light makes possible the generation of variable delays with much reduced amplitude change. We experimentally demonstrate it in this paper using a simple but considerably powerful configuration, with signal amplitude controlled all along the delaying fiber. In addition the same scheme can be used to generate zero-loss fast light and signal advancement, by simply swapping the spectral positioning of Pump 1 and Pump 2. The amount of broadening possible for both pumps remains limited by the Stokes and Anti-Stokes spectral overlapping, like in the single pump standard non-compensated scheme [8]. It must be pointed out that the broadened SBS Pump 2 can be replaced by any broadband amplification process based on another type of interactions such as Raman scattering and parametric amplification, but also using doped fibers. The operation of the delay line would be in this case less convenient, since the Probe signal and the SBS Pump 1 will both be subject to the bidirectional broadband gain. This demonstrates the key role and the excellent suitability of SBS for the generation of slow &

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fast light in optical fibers, thanks to its directivity and its unique narrowband and flexible spectral property.

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