Self-advanced fast light propagation in an optical fiber based on Brillouin scattering

Sanghoon Chin, Miguel Gonzalez-Herraez[1], and Luc Thévenaz

Ecole Polytechnique Fédérale de Lausanne, STI-GR-SCI Station 11, CH-1015 Lausanne, Switzerland
[1]Department of Electronics, University of Alcalá de Henares, E-28805 Madrid, Spain
sanghoon.chin@epfl.ch, miguelg@depeca.uah.es, luc.thevenaz@epfl.ch

Abstract: We experimentally demonstrate an extremely simple technique to achieve pulse advancements in optical fibers by using both spontaneous amplified and stimulated Brillouin scattering. It is shown that the group velocity of a light signal is all-optically controlled by its average power while it propagates through an optical fiber. The signal generates an intense back-propagating Stokes emission that causes a loss on the signal through depletion. This narrowband loss gives rise to a fast light propagation at the exact signal frequency. The Stokes emission self-adapts in real time to the Brillouin properties of the fiber and to a wide extent to the signal bandwidth.

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

The dynamic control of the speed of a light signal propagating through an optical medium by an active modification of the group velocity, commonly known under the denomination of "slow & fast light", finds an interesting field of application in optical networking, microwave photonics and photonic signal processing [1-4]. Several principles have been demonstrated to realize this control, among them, electromagnetically induced transparency (EIT) [2] and coherent population oscillation (CPO) [3-4]. These phenomena require specially prepared media (atomic vapors, crystals, rare earths) with long-lifetime transitions. A promising way to make these techniques more practical is to exert this control in a conventional optical fiber. Demonstrations of this possibility have been carried out along the past three years, using different amplification phenomena such as stimulated Brillouin scattering (SBS) [5-6], stimulated Raman scattering (SRS) [7] and parametric amplification [8]. Among these techniques, SBS presents two main advantages: first, given its large efficiency, an extremely wide group velocity control can be carried out at still reasonable power levels [9]; second, the spectrum of the interaction can be engineered to fit different requests in terms of bandwidth and distortion of the signal [10-13]. For instance, a two-tone pump spectrum can give rise to fast light in gain regime if the frequency separation between the pumps is correctly chosen [10]. Moreover, the bandwidth of SBS-induced gain can be increased arbitrarily by actively broadening the pump spectrum using a random modulation of the pump laser current [11], to ultimately reach a 12 GHz bandwidth [12]. The possibility to spectrally superpose Brillouin gain and loss spectra gives another degree of freedom to design innovative schemes, such as a further extension of the bandwidth up to 25 GHz [13] and the generation of delays without amplitude change [14].

These former results show that stimulated Brillouin scattering offers an unmatched flexibility for an all-optical control of the pulse delay in a fiber. However, considering practical issues, this approach shows two actual drawbacks: first, this scheme inevitably requires an external pump source; second, the frequency separation between the pump and probe lasers has to be constant and precisely controlled within typically a 1 MHz uncertainty. These requirements force a certain complexity in the experimental system, which should be preferably avoided in many practical applications. In this paper, we demonstrate that a light signal with a sufficient average component can make itself speed up along the fiber without any external pump source. The working principle is the following: when the signal power grows beyond a certain critical power - commonly denominated Brillouin threshold - a significant Stokes component is generated at a frequency downshifted ν_B below the signal. This Stokes wave, in turn, acts as a Brillouin pump to create an absorption peak in the transmission spectrum of the fiber at the signal wavelength, hence creating advancement on the signal pulse. In short, simply controlling the power of the signal entering the fiber eventually determines its advancement. This configuration is considerably simpler than all the previously reported techniques and may serve as a practical basic concept for several applications.

2. Principle

Stimulated Brillouin scattering in optical fibers results from the interference of two counter-propagating waves. For a definite frequency difference between the waves $\nu_B = \nu_{pump} - \nu_{probe}$ called the Brillouin shift, this interference generates an acoustic wave through the process of electrostriction. This acoustic wave, in turn, causes a periodic modulation of the refractive index which eventually transfers a fraction of the pump intensity into the probe wave. As the probe wave grows, the amplitude of the interference is larger, the acoustic wave is more sustained and the scattering process turns more efficient. This stimulation effect globally

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manifests through an exponential growth of the probe wave. Thus, SBS can be considered as a narrowband amplification process, in which a strong pump wave produces a narrowband gain (~30 MHz) in a spectral region around ν_{pump}-ν_B. Following a similar reasoning, the power transfer from the pump to the probe can be assimilated to a loss for the pump. So, by simply swapping the relative spectral positions of pump and probe, the pump will cause a narrowband loss for the probe around $\nu_{pump}+\nu_B$. These narrowband gain/loss processes are associated to sharp index changes, around which there is a positive/negative variation of the effective group index in the fiber [1,5].

It is important to point out, however, that the process of SBS may be initiated without the need of an external probe wave. The background energy present in the fiber in ambient conditions causes the presence of thermally activated acoustic waves that spontaneously scatter the light from the pump. This noise-scattered seed light initiates the stimulation and is thus gradually amplified if it lies within the SBS gain spectrum. This can eventually lead to a considerable amount of power that is back-reflected at the Stokes wavelength ν_{pump}-ν_B. A useful quantity in this case is the Brillouin critical power P_c, which is conventionally defined as the power of the input CW light necessary to have an equal amount of power present in the backscattered Stokes wave in the fictitious case of an absence of depletion. For a uniform fiber, this critical power can be estimated [15] as $P_c=21A_{eff}/(g_B L_{eff})$, where g_B is the Brillouin gain coefficient, A_{eff} is the nonlinear effective area of the fiber and L_{eff} is the nonlinear effective length. In long conventional optical fibers with $L>L_{eff}$, this critical power is about 5 mW at a wavelength of 1550 nm and can thus be easily reached using off-the-shelf DFB lasers.

The basic idea of the self-induced fast light scheme is to avoid using a distinct pump wave to modify the signal propagation conditions through SBS. This is simply realized by delivering a sufficiently powerful average signal into the fiber, above the Brillouin critical power P_c. Seeded by noise, the process of stimulated Brillouin scattering will generate a substantial Stokes signal, which in turn will induce through depletion a narrowband loss for the signal, as depicted in Fig. 1. Associated to this narrowband loss, a spectral region of anomalous dispersion is induced, in which the temporal envelope of the signal will experience advancement through fast light.

The advantage of this configuration is that the signal is continuously and accurately centered in the spectrum of the loss resonance created by the spontaneously amplified Stokes wave. The pump-signal frequency difference automatically compensates for any environmental and wavelength changes and remains perfectly stable without the need of any optical component or instrument (such as external modulators, microwave generators, etc.) typically used in other configurations [5,9,10,14]. Moreover, in case of very large gain as in the present situation, the state of polarization of the Stokes wave is precisely identical to that

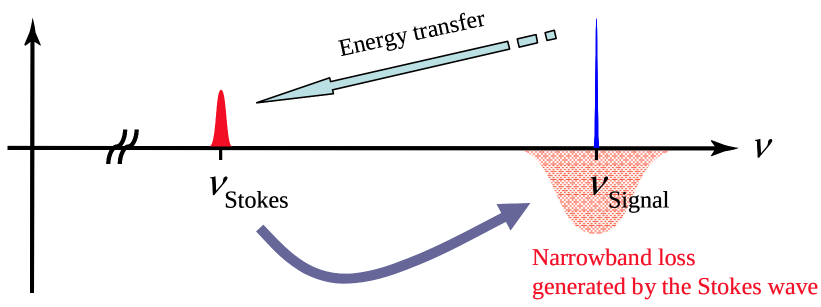

Fig. 1. Principle of the configuration to generate self-advanced fast light. The signal is powerful enough to generate a strong amplified spontaneous Stokes wave, which in turn depletes the signal wave. The depletion is assimilated to a narrowband loss spectrum.

of the signal at the fiber input since the SBS interaction coherently transfers photons from the

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pump to the Stokes wave and preserves their state of polarization [16]. Thus, in these conditions, the polarization of the strongly amplified Stokes wave experiences a pulling effect and eventually aligns to the pump polarization. This holds for a common standard fiber with a reasonably low birefringence value. This secures a maximum efficiency and stability for the interaction, and hence the highest possible advancement for a given input power.

When addressing the delay-bandwidth characteristics and the efficiency of a slow & fast light scheme, it is important to know the spectral width of the Brillouin resonance. The bandwidth of the gain/loss process is obtained from the convolution of the intrinsic Brillouin spectral distribution with the pump spectrum [11]. In our case, it is important to realize that the Stokes signal is not purely monochromatic, since it builds up from a noise-seeded SBS process and will therefore present a certain spectral distribution [17]. For low input power the spontaneous Brillouin noise shows a linewidth close to the intrinsic Brillouin linewidth $\Delta\nu_B$. However, for higher input power, the linewidth experiences a dynamic narrowing. This narrowing stabilizes when the critical power is reached and a significant depletion of the input signal is observed [17]. In our case, significant advancement of the signal starts to take place when the signal power exceeds the Brillouin critical power, hence when significant pump depletion starts to occur. In these conditions, the spectral width of the amplified spontaneous Brillouin emission should remain moderate and constant for all input powers [17]. We must therefore expect a power-invariant loss spectral distribution for the signal, since it is essentially given by the convolution of the Stokes wave spectrum with the natural Brillouin gain, both being constant for all the relevant input powers in the present experimental conditions.

The power of the signal must also be considered as constant when time-averaged during fiber transit, so that an amplified spontaneous Stokes emission showing a constant power is generated and no time jitter is observed on the delays. Practically this condition requires that the fiber length must be much longer than the typical periodicity of the signal, or equivalently a large number of symbols (> 100-1000) forming the data pattern must simultaneously propagate through the fiber. Under this condition each separate symbol in the data stream taken individually has a negligible impact on the amplitude of the Stokes wave and therefore experiences a Brillouin loss actually similar to that produced by an external constant pump. This makes the system behave identically to a standard Brillouin fast light configuration in terms of distortion and limitation.

3. Experiments and Results

The experimental setup realized to demonstrate the self-advanced fast light through SBS is shown in Fig. 2. A 12-km-long conventional dispersion shifted fiber (DSF) with a Brillouin shift of 10.6 GHz and a FWHM gain bandwidth of approximately 27 MHz is used as the SBS gain/loss medium. To generate the signal we used a commercial distributed feedback laser diode (DFB-LD) operating at a wavelength of 1532 nm. The output of the laser is modulated using an external electro-optic modulator to produce a pulse train with a width of 45 ns (FWHM) at a 5 kHz repetition rate. With this periodicity, only one pulse is present at a time

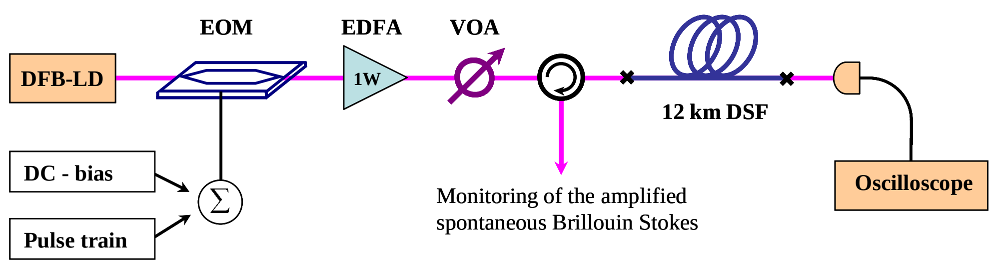

Fig. 2. Experimental configuration to realize the self-pumped pulse advancement based on both amplified spontaneous and stimulated Brillouin scattering. EOM; electro-optic modulator, EDFA; Erbium-doped fiber amplifier, VOA; variable optical attenuator, DSF; dispersion shifted fiber.

#94139 - $15.00 USD Received 20 Mar 2008; revised 25 Jul 2008; accepted 25 Jul 2008; published 30 Jul 2008

over the entire optical fiber, so that any cross-interaction between adjacent pulses during propagation is avoided at a first stage. The signal includes a definite DC component obtained simply by adjusting the DC bias applied to the EOM. This DC component is essentially responsible for the creation of the Stokes wave. As we will show below, in a realistic fiber system a sufficiently long pulse sequence present in the fiber would equally generate the Stokes component responsible of the pulse advancement. The DC power is approximately 14 % of the peak power of the pulse, but creates a much larger integrated gain over the fiber length considering the very low pulse repetition rate. Then this compound signal is strongly boosted using a high power erbium-doped fiber amplifier (EDFA) with ~30 dBm saturation power before it is launched into the DSF. The signal power is controlled with a variable optical attenuator (VOA) after being amplified by the EDFA. The strong DC component present on the signal generates a strong backward Brillouin Stokes at a frequency downshifted ν_B below the pulse signal frequency. This Stokes wave causes an absorption peak in the spectral transmission of the fiber at the frequency of the input signal, which consequently experiences fast light conditions.

This is observed at the fiber output by measuring with a fast detector the temporal advancement of the pulse signal for different input signal powers. To perform this measurement we controlled the amplitude of the pulse at the input of the detector with a variable optical attenuator so as to avoid any possible biasing of the trace from an amplitude-dependent time response of the detector. The higher the input power, the stronger the Stokes wave, the deeper the peak absorption is and the faster the pulse will travel.

To back up the discussion on the bandwidth developed in the previous section, we characterized the linewidth of the Stokes wave with respect to the signal power. The spectral width of the Stokes wave was measured by the delayed self-heterodyne method [18]. This method is an interferometric method, and is based on a Mach-Zehnder interferometer in which one arm contains a frequency shifter (EOM2) and the other is used as a delay line to break the coherence of the analyzed beat signal. The beating is recorded using a fast detector connected to an electrical spectrum analyzer. The Stokes power as a function of the input signal power is shown in Fig. 3(a). We can see that there is no significant Stokes component below the Brillouin critical power, while an abrupt change is observed over this threshold power. For higher signal power all the light intensity in excess of the threshold power is transferred to the Stokes waves, making the output signal power saturate at a constant value. For even higher input power exceeding twice the Brillouin threshold the Stokes waves is powerful enough to generate its own Stokes wave co-propagating with the signal. This turning point at approx. 24 dBm input power is observed as an apparently resumed growth of the signal output power, as clearly shown in Fig. 3(a). Figure 3(b) shows the spectral profiles of the generated Stokes wave for different input signal powers, all of them over the SBS critical power. The spectra

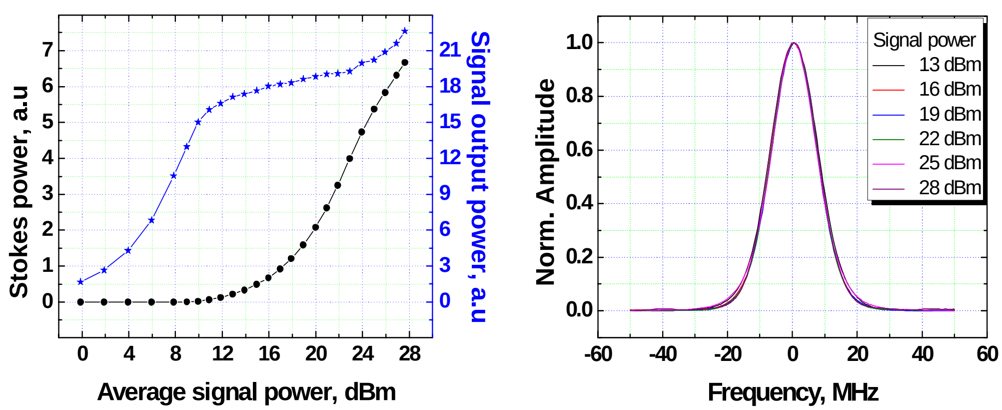

Fig. 3. (a). measured optical powers of the Stokes waves and transmitted signals (b) linewidths of the generated Brillouin Stokes waves recorded in the ESA, by use of the delayed homo-heterodyne system.

#94139 - $15.00 USD Received 20 Mar 2008; revised 25 Jul 2008; accepted 25 Jul 2008; published 30 Jul 2008

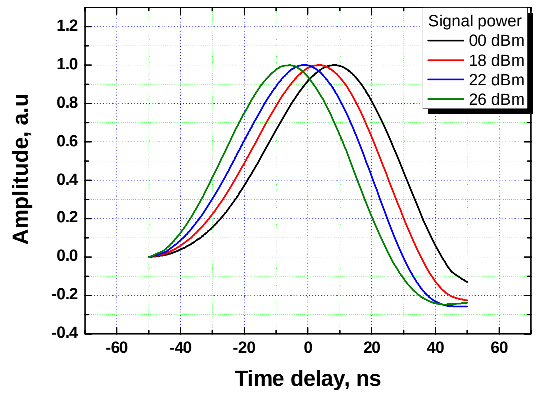

Fig. 4. Temporal traces of the signal pulse after propagating through the dispersion shifted fiber for different input signal powers, showing clear advancements.

show no linewidth change of the Stokes wave for all the relevant input powers, hence we can safely consider that the spectrum of the loss process will remain similar for all input powers, generated by a lightwave showing a linewidth of approximately 10 MHz.

In previous realizations [5,6,9] the pulse delay induced by the SBS effect was typically measured as a function of the Brillouin gain/loss, as a consequence of the simple linear relationship between these two quantities. In our experiment, however, it turns out to be conceptually inappropriate since the signal pulse experiences fast-light propagation with no independent pump source. Additionally, the signal loses part of its power as a result of the Brillouin loss and saturates to a roughly constant value. Therefore, a direct measurement of advancement as a function of loss experienced by the signal is of limited interest and can not be easily extracted from the raw data. A more interesting quantity to plot, however, is the delay as a function of the input signal power. Figure 4 shows the measured time waveforms of the signal pulses for different average powers of the input signal, ranging from 0 dBm to 28 dBm. It is clearly observed that the pulse experiences more advancement as the input power increases. Additionally, in all cases, the signal pulse experiences low distortion. The advanced pulses show a slightly sharper leading edge and a longer trailing edge, consistent with previous observations in SBS fast light [9]. The largest advancement induced by the proposed scheme is 12 ns obtained with a 28 dBm signal power and corresponds to a fractional delay of 0.26. This power, in our case, was limited by the saturation power of the EDFA. Longer delays could eventually be realized in this method with an EDFA with higher

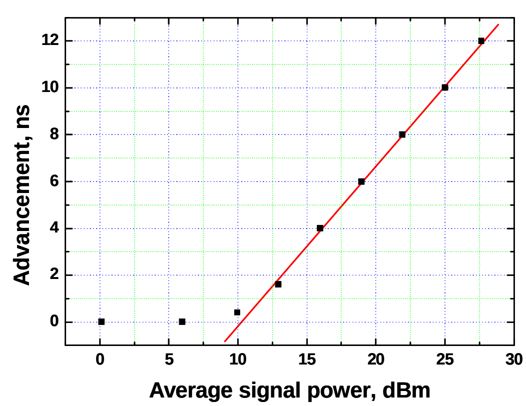

Fig. 5. Temporal advancements of the signal pulses as a function of the signal average power.

#94139 - $15.00 USD Received 20 Mar 2008; revised 25 Jul 2008; accepted 25 Jul 2008; published 30 Jul 2008

saturation power or with a fiber showing a smaller effective area. Figure 5 shows the advancement observed on the signal as a function of the input power. To determine the amount of signal advancement we used the position of the peak of the pulse. Notice that for low power levels, there is no visible advancement, since there is no significant loss of the signal below the Brillouin critical power. When the signal power exceeds this critical value, the pulse train immediately experiences an observable advancement. In the range of measured values, the advancement depends logarithmically on the input power, with a slope efficiency of 0.69 ns/dBm.

This logarithmic dependence is actually a direct consequence of the total power transfer from the signal to the Stokes power above the Brillouin critical power P_c. The effective total loss A experienced by the signal is defined as

$$\frac{P_{out}}{P_{in}} = e^{-A}$$

where P_{in} and P_{out} represents the input and output signal power, respectively. Since above the Brillouin threshold the signal output power P_{out} saturates to a constant value P_{sat}, the effective loss simply depends on the input signal power P_{in} following this relationship:

$$A(P_{in}) = -\ln\left(\frac{P_{out}}{P_{in}}\right) = -\ln\left(\frac{P_{sat}}{P_{in}}\right)$$

The temporal advancement being proportional to the effective total loss A and P_{sat} being constant, the logarithmic dependence on the input power comes out immediately from this simple description.

To demonstrate that this technique can also be used for a data stream with negligible DC component we modified the pulse repetition rate to 20 MHz, so that it reasonably simulates a real sequence of bits when averaged over the fiber length. The pulses in this case have a FWHM of 14.22 ns, hence the duty cycle is 30%. The DC component is reduced to a negligible fraction of the pulse peak power in this case. Figure 6(a) shows the pulse train for 2 different signal powers – one below the critical power and one at the maximum possible value using our setup – and the pulse advancement is again clearly visible. Figure 6(b) shows the advancement as a function of the signal power, with a maximal obtained fractional delay of 0.42. The slope is in this case 0.35 ns/dBm. It must be pointed out that the power of the data stream time-averaged over the fiber length must remain constant to avoid any time jittering at the output, requiring a steady fraction of bits "1" with respect to the total number of bits.

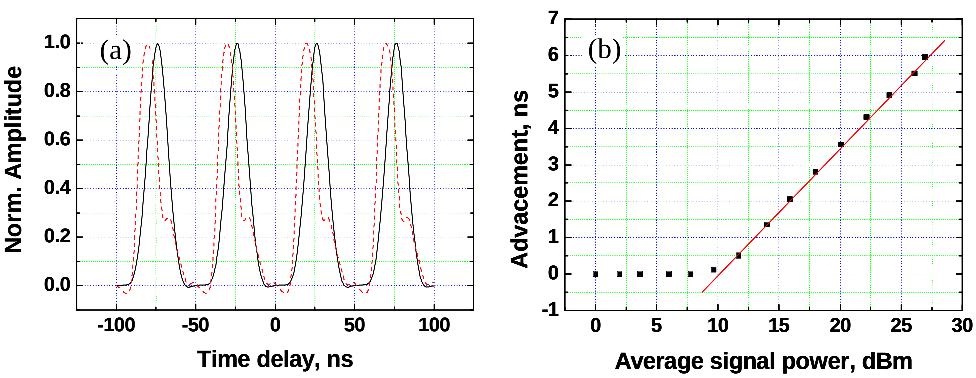

Fig. 6. (a). Temporal traces of the data streams for a signal power below the critical power (solid line) and at maximum signal power realized in our setup (dashed line). (b) Signal advancement as a function of the average signal power, showing the logarithmic dependence over the Brillouin critical power at 10 dBm.

#94139 - $15.00 USD Received 20 Mar 2008; revised 25 Jul 2008; accepted 25 Jul 2008; published 30 Jul 2008

The main limit for the maximum possible advancement in this configuration is caused by the onset of the 2nd order SBS amplified Stokes emission. Once the backward Stokes reaches its own critical power for SBS, there will be a forward Stokes wave downshifted by $2\nu_B$ below the frequency of the input signal. This wave will deplete the backward Stokes wave and hence make the advancement saturated. This places a fundamental limit to the range of signal power suitable to produce a delaying effect.

Finally a last aspect of self-pumping was investigated related to the capability of the Stokes amplified emission to adapt its spectral width to the signal bandwidth. For this purpose we observed the Stokes emission generated by a pulse train with an averaged power well above the Brillouin critical power P_c. The initial pulse width was 50 ns at a repetition frequency of 4 MHz, corresponding to a normalized repetition rate of 5. Such a signal shows a measured FWHM bandwidth of 9 MHz that is substantially lower than the Brillouin natural linewidth. Then we decreased the pulse width and adapted proportionally the repetition frequency to maintain a constant normalized repetition rate. This way the average pump power is kept constant and the only modified relevant signal characteristic is its bandwidth. Figure 7(a) shows the measured Stokes spectra for different pulse width. From a floor value of 10 MHz the Stokes linewidth clearly self-adapts to the incremental broadening of the signal, as illustrated in Fig. 7(b). It must be pointed out that the Stokes linewidth represents only a fraction of the input signal bandwidth. We could extrapolate from the measurements shown in Fig. 7(b) that this fraction corresponds asymptotically for a wideband signal to about 45% of its bandwidth. Even after convolution with the natural Brillouin spectrum this fractional linewidth has certainly a substantial impact on the pulse distortion.

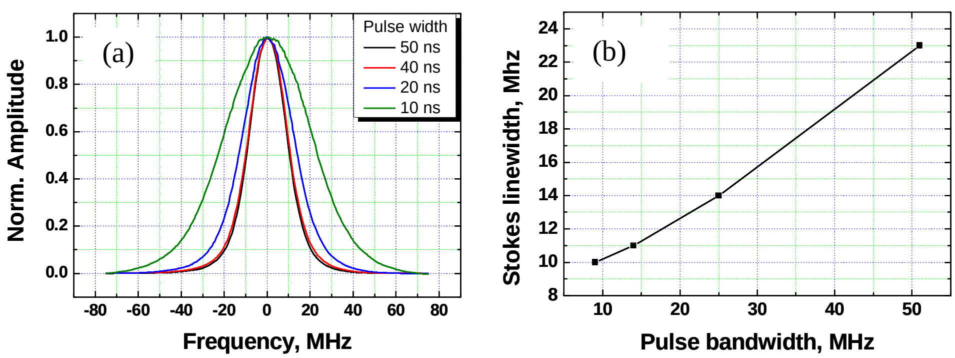

Fig. 7. (a). Measured spectra of the Stokes emission by the delayed self-homodyne technique, for different pulse widths at a constant normalized repetition rate. (b) Measured Stokes linewidth as a function of the measured signal bandwidth.

4. Conclusions

In this paper the possibility to generate tunable delays in optical fibers based on Brillouin slow & fast light without additional pumping source is experimentally demonstrated. Through the process of spontaneous amplified Brillouin scattering the signal generates a Stokes wave that in turn depletes the signal and creates a narrowband loss. The delaying effect only depends on the Stokes wave power that is simply varied by changing the average signal input power. The implementation of such a delaying scheme turns out to be extremely simple and requires a very limited number of optical devices, since the generation of the pump and the delaying effect are all produced by a single segment of optical fiber. This inherent simplicity should have an evident positive impact on the stability, the reliability and the economic dimension of the actual delay line. This scheme offers also some clear advantages, such as the perfect self-adaptation of the Stokes emission to spectrally match the loss resonance with the signal spectrum, even in changing environmental conditions. Moreover the self-generated pump

#94139 - $15.00 USD Received 20 Mar 2008; revised 25 Jul 2008; accepted 25 Jul 2008; published 30 Jul 2008

spectrum adapts to a large extent to the average bandwidth of the signal, thus maintaining the complexity low even for broadband signals.

The main limitations observed during our experiments are related to the requirement of a permanent constant average power in the data stream to avoid fluctuations in the signal delay and amplitude. Other limitations come from a maximal generated delay shorter than in conventional implementations as a result of the onset of the 2^{nd} order Stokes and from a linewidth of the resonance that only covers a fraction of the signal bandwidth.

The principle is equally demonstrated for isolated pulses and for pulse trains at high repetition rate, anticipating its suitability for an implementation in real digital or analog systems.

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