Complete compensation of pulse broadening in an amplifier-based slow light system using a non-linear regeneration element

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Abstract: We experimentally demonstrate complete compensation of pulse broadening in an amplifier-based slow light system. The configuration of the delay line basically consists of two stages: a conventional Brillouin slow light system and a nonlinear regeneration element. Signal pulses experienced both time delay and temporal broadening through the Brillouin delay line and then the delayed pulses were delivered into a nonlinear optical loop mirror. Due to the nonlinear response of the transmission of the fiber loop, the inevitably broadened pulses were moderately compressed in the output of the loop, without loss in the capacity to delay the pulses. The overall result is that, for the maximum delay, the width of the pulse could be kept below the input width while the time delays introduced by the slow light element were preserved. Using this delay line, a signal pulse with duration of 27 ns at full width at half maximum was delayed up to 1.3-bits without suffering from signal distortion.

OCIS codes: (060.2310) Fiber optics; (290.5900) Scattering, stimulated Brillouin; (060.4370) Nonlinear optics, fibers; (350.5500) Propagation; (190.3270) Kerr effect

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#116964 - $15.00 USD Received 9 Sep 2009; revised 26 Oct 2009; accepted 30 Oct 2009; published 16 Nov 2009

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1. Introduction

Slow light has important potential implications in modern technologies oriented towards high capacity networks such as all-optical signal processing, optical buffers, optical memories and quantum computing [1]. In recent years, a number of slow light systems have been experimentally realized based on different physical phenomena in optical media, such as electromagnetically-induced transparency, coherent population oscillations, optical parametric amplification and stimulated scattering processes [2]. All these slow light schemes share a common feature making the essence of the slow and fast light generation in optical media: the presence of one or multiple strong spectral resonances to obtain a highly dispersive material. Unfortunately, the sharp change in refractive index is also accompanied with an inevitable dispersion (in amplitude and phase) that mostly manifests as pulse broadening. As a result, the larger the delay in the slow light medium, the more broadening in the output pulse. In order to overcome this delay-distortion trade-off, several linear slow light schemes have been theoretically and experimentally investigated [2-13]. In particular, tailoring the shape of the spectral resonance to optimize the dispersive properties of the material could partially reduce the induced distortion while keeping the fractional delay. However, this approach could not fully eliminate the induced distortion, thus the maximum achievable pulse delay remains limited to a few pulse durations. In parallel, the limits of distortion and delay have been explored for several kinds of slow light systems [14-17], and recent studies seem to indicate that linear slow light systems will never be candidates for making distortionless (or zero-broadening) slow light systems [17]. Nevertheless, the vast majority of the slow light systems proposed up to now in the literature can be considered linear in terms of the signal propagation. Therefore, a general scheme to achieve slow light without distortion for any arbitrary fractional delay is still under investigation, but the results of these papers seem to indicate that nonlinear elements should be essential for this task. In [18], a possible solution to mitigate the broadening effect was put forward using a depleted (therefore nonlinear) Brillouin amplifier as slow light system. Even though the pulse broadening issue was improved, the broadening compensation was certainly not complete, and the saturation in the amplification had the unwanted outcome of reducing also the delaying effect.

In this paper, we propose and experimentally demonstrate a new configuration to compensate the inherent signal broadening that is observed in any slow light system. Our demonstration is based on an all-fiber setup, rendering the system very attractive for future applications in the field of optical communications. It makes use of the combination of a conventional Stimulated Brillouin Scattering (SBS)-based linear slow light system and a nonlinear optical fiber loop mirror (NOLM) as the broadening compensation element. The NOLM plays the role equivalent to a fast saturable absorber. In the Brillouin slow light segment, the signal pulse experiences both a time delay and the usual broadening. Then this delayed pulse is delivered into the nonlinear optical loop mirror, where it experiences a compression as a result of the nonlinear transmission (the peak of the pulse is more

#116964 - $15.00 USD Received 9 Sep 2009; revised 26 Oct 2009; accepted 30 Oct 2009; published 16 Nov 2009

transparently transmitted than the edges). In our experiment, we could effectively achieve no pulse broadening for a fractional delay above unity in the SBS slow light delay line. Additionally, this regeneration element can eliminate most of the background noise introduced by the Brillouin amplifier when the pulse is “off”, therefore improving the contrast between the ones and the zeros in a transmission system. There is in principle no limitation to cascade this system and achieve large fractional delays with minimized distortion.

2. Principle

Stimulated Brillouin scattering in optical fibers results from the interference of two counter-propagating waves (a strong pump and a weak probe wave) that couples through the intercession of an acoustic wave. For a definite frequency difference between the two waves $\nu_B = \nu_{pump} - \nu_{probe}$ called the Brillouin shift, the beating signal between the two optical waves reinforces the acoustic wave. In addition, through the process of electrostriction, the material density is periodically modulated along the fiber so as to lead to a periodic modulation of the refractive index. In consequence, a fraction of the pump intensity is transferred 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 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], referred to as Brillouin slow light and fast light, respectively. Even though the process itself is non-linear, it can be shown that the effect of the amplification/loss on the signal wave can be treated as a linear effect (in absence of pump depletion) and therefore modeled through a linear transfer-function approach [17].Thus, as a linear low-pass system, the signal pulse is broadened and this limits the maximum delay that can be achieved with a reasonable distortion. To avoid this effect, and as already pointed out in [17], one can place a nonlinear regeneration element (for instance, a saturable absorber) at the output of the slow light system. The role of this nonlinear element can be interpreted in both time and frequency domains. A pulse passing through a saturable absorber should be sharpened, since the peak has a higher intensity than the wings and therefore experiences less distortion. Since this nonlinear element plays the role of pulse sharpening, the spectrum of the signal in the output of nonlinear element turns to be broader. As a result, the frequency components that have been filtered out by the slow light medium are regenerated, restoring the signal bandwidth. This paper validates this idea in a simple, all-fiber configuration, which may be useful for future applications.

The experimental scheme comprises two basic building blocks: an SBS slow light delay line and a nonlinear optical loop mirror (NOLM) that acts as a regeneration element. Upon propagation through the SBS slow light line, the signal pulse essentially experiences distortion accompanied with signal delay. In the proposed configuration, the NOLM acts similarly to a fast saturable absorber. The transmission of the NOLM is larger for higher input powers and decays rapidly as the input power is reduced. When a pulse enters into the compensation element, the peak of the pulse experiences a larger transmission coefficient than the wings, leading to a sharpening in its shape. By only using the input power to the NOLM as control variable, we can also accommodate the sharpening of the pulse in the NOLM, and potentially we can think on achieving a complete regeneration of the pulse. This way the system can give rise to a compensation of pulse broadening caused in the SBS slow light line, so that one can achieve pulse delays with no broadening within a limited range of delay.

The NOLM basically consists of a Sagnac loop in which an attenuator is placed at one loop end and thus introduces a large power imbalance between the clock-wise and counter-clockwise fields while they propagate in the loop. A polarization controller was used in the

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loop to match the states of polarization (SOP) so as to maximize the visibility of the interference and secure a total absence of transmission at low powers. In linear operation, the Sagnac mirror acts as a perfect mirror. The input pulse is split by a directional coupler into two counter-propagating electric fields, as shown in Fig. 1. The two fields are in turn re-combined at the coupler after propagation through the optical loop. Since they travel the same path but in opposite direction, the optical path length is identical to both counter-propagating fields, resulting in the same linear phase shifts. As a result, the input pulse is totally reflected into the input port. Therefore, at low input powers the loop acts as a perfect mirror, and no light exits through the output port. In the high power regime, however, the refractive index of the fiber depends on the light intensity. This means that the imbalance in the optical power of the two arms caused by the attenuator will lead to a difference in the effective optical path length for the clockwise and counter-clockwise pulses [19].

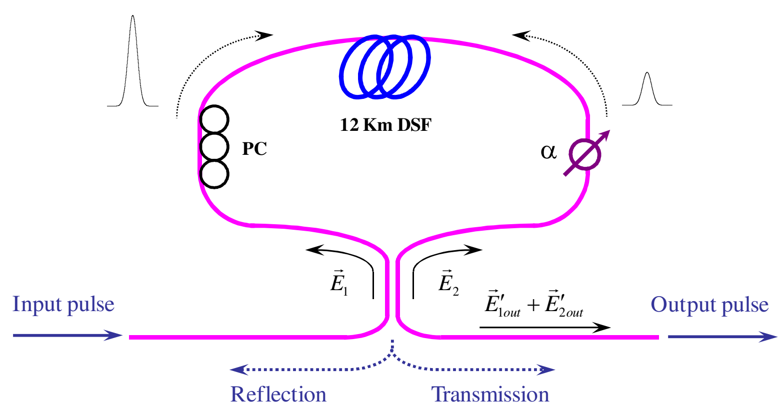

Fig. 1. Schematic diagram of an attenuation imbalanced nonlinear optical fiber loop to compress the shape of a pulse. E_1 and E_2 present clock and counter-clock wise electric fields of signals, respectively. DSF; dispersion shifted fiber, PC; polarization controller and α; an attenuation factor.

In this experiment, the input light was equally split as required for maximum contrast, but a 1 dB attenuation was set for the counter-clock wise field prior to its propagation through the loop using a variable optical attenuator. In addition, a 12-km dispersion shifted fiber (DSF) was used as a nonlinear medium over which the two fields experience a differential phase shift, mainly caused by Kerr effect. The clock and counter-clockwise electric fields E_1 and E_2 before entering the DSF can be written as:

$$E_1 = \sqrt{1/2}\,A_{in} \quad \text{and} \quad E_2 = i\sqrt{\alpha/2}\,A_{in}$$

where A_{in} presents the amplitude of the input electric field and α is the attenuation factor for the E_2. Upon recombination in the coupler, the signal at the output port will depend on the input power and the power imbalance between the two arms. In this circumstance, the electric fields after a single pass via the loop are given by the expressions:

$$E'_{1out} = \frac{\sqrt{\alpha}}{2} A_{in} \exp\left[i\frac{1}{2}\varphi\right] \quad \text{and} \quad E'_{2out} = -\frac{\sqrt{\alpha}}{2} A_{in} \exp\left[i\frac{\alpha}{2}\varphi\right]$$

The nonlinear phase shift φ is defined as $\varphi = \gamma P_o L_{eff}$ where γ is the nonlinear coefficient, P_o is the optical power of the light at the input port and L_{eff} is the effective fiber length. γ is typically 2 $W^{-1}km^{-1}$ in DSFs, the effective length of the DSF in this experiment was 4.5 km and the peak power of the input pulse was 185 mW. Considering a 1 dB power imbalance between the arms, these values result in a small differential nonlinear phase shift. The electric field of the transmitted light T_E can be written as:

$$T_E = i\sqrt{\alpha}A_{in}\exp\left[i\frac{\varphi}{4}(1+\alpha)\right]\sin\left(\frac{\varphi}{4}(1-\alpha)\right)$$

and the transmission coefficient can be obtained by the modulus of T_E:

$$T = \left|T_E\right|^2 = \alpha\sin^2\left(\frac{\varphi}{4}(1-\alpha)\right) \approx \frac{\alpha(1-\alpha)^2}{16}\varphi^2 \quad \text{for } \frac{\varphi}{4}(1-\alpha) \ll 1$$

The system turns out to be equivalent to a saturable absorber: the transmission grows for higher input powers, with a cubic dependence on the power for small accumulated nonlinear phase shifts. Since the power in the peak of the pulse is larger than in the wings, the output pulse will be sharper than that at the input, resulting in pulse compression [20]. As shown in the expression of T_E, the phase of the output pulse after transmitting through NOLM is also altered by self-phase modulation, given as:

$$\Delta\varphi(t) = \frac{\pi}{2} + \frac{\pi(1+\alpha)n_2L}{2\lambda}\left|A_{in}(t)\right|^2,$$

where n_2 is nonlinear-index coefficient. It leads to a frequency chirp imposed through the pulse, given by the time derivative of the phase shift:

$$\delta\omega(t) = \frac{\pi(1+\alpha)n_2L}{2\lambda}\frac{d}{dt}\left|A_{in}(t)\right|^2.$$

Assuming that the amplitude of the input electric field A_{in} is Gaussian, in the center of the transmitted pulse a linear frequency chirp will be predominantly present with negative slope. It shows that the delayed pulse can be further compressed by placing a dispersive medium with anomalous dispersion such as dispersion compensating fiber. This type of extra pulse compression would be probably minor in our setup as far as the pulses used are relatively long (slow variation). However, it may turn to be important for pulse delay in high data rate.

3. Experiments and results

The schematic diagram of our experimental setup is depicted in Fig. 2. 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 A commercial distributed feedback (DFB) laser diode operating at 1532 nm was used as the light source and its output was split using an optical coupler. Then one branch 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 before entering into the delaying fiber segment. The other branch was modulated through an electro-optic Mach-Zehnder intensity modulator (EOM) at the Brillouin frequency shift so as to generate two first-order sidebands. The DC bias of the modulator was adequately set to obtain complete suppression of the carrier. Therefore, only two sidebands were present at the output of the modulator. The lower-frequency sideband was then precisely isolated by a fiber Bragg grating via a circulator and was optically gated using a fast external modulator to generate the signal pulse train. Consequently, a signal pulse train was generated downshifted in frequency with respect to the pump by the Brillouin shift. The signal pulses showed duration of 27 ns FWHM at a repetition rate of 200 kHz.

To produce time delays, the signal pulse was sent into the SBS delay line while the pump power was increased from 0 to 30 mW. Figure 3(a) shows the normalized time waveforms of the signal pulses at the output of the Brillouin delay line. As in any typical Brillouin slow light

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system, it is clearly observed that the time delay increased as a function of the pump power. Also, the pulse exiting from the delay line was temporally both delayed and broadened with respect to the pump power. This way the largest pulse delay achieved was about 36 ns (corresponding to 1.3-bits delay) at the pump power of 30 mW and the delayed pulse was significantly broadened by factor 1.9. After passing through the delay line, the delayed pulse was amplified using another EDFA in order to saturate its power, and delivered into the nonlinear loop. In practice, the NOLM acts as a saturable absorber as previously described. Consequently, the shape of the broadened pulse was sharpened at the output, as shown in Figure 3(b). Moreover, it must be pointed out that the unwanted background components imposed onto the pulse train (mainly amplified spontaneous emission from the EDFAs and the

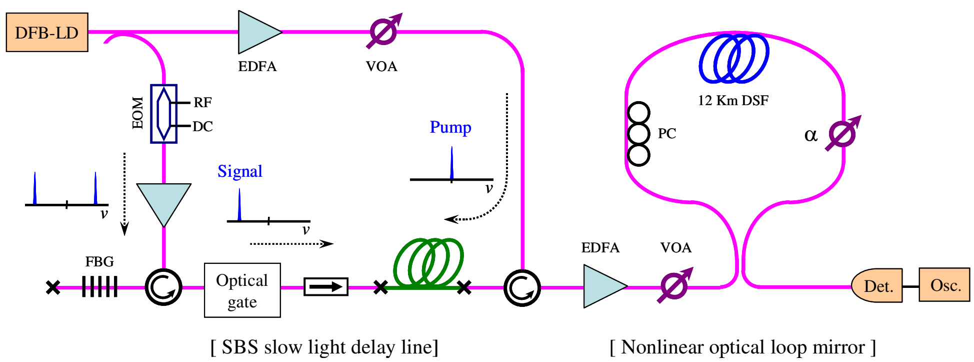

Fig. 2. Experimental setup to produce non-broadening pulse delays, by combining a nonlinear generation element with a typical Brillouin slow light system. EDFA; erbium doped fiber amplifier, EOM; electro-optic modulator, FBG; fiber Bragg grating, VOA; variable optical attenuator, DSF; dispersion shifted fiber, PC; polarization controller and α; an attenuation factor.

Brillouin amplifier) were cleaned up since they were rejected for transmission. It is clearly observed that the output pulse is compressed at the output of the loop, nevertheless fully preserving the time delays achieved in the SBS delay line. Figure 4 shows the measured fractional delay and signal broadening as a function of signal gain. This system allows producing fractional delays of up to 1.3-bits without any broadening. This result is fully consistent with the prediction for a transmission depending cubically on the intensity, which gives a compression by a factor $3^{-1/2}$ when applied to a pulse with a Gaussian intensity profile. Of course the non-delayed pulse is also compressed, but this should not be an issue in detection, since the detection system is inherently band-limited. Another advantage concerns the signal-to-noise ratio of the setup. The contrast in dB between signal “on” and “off” states is expected to triple in logarithmic scale since the intensity at the output of the NOLM follows a cubic law with respect to the input power. We observed that the output signal contained amazingly very clean zero background level, which is rather unusual in Brillouin amplifier setups. This zero-background level can be very helpful in real transmission systems to enhance the contrast between the “on” and “off” states in the detection process.

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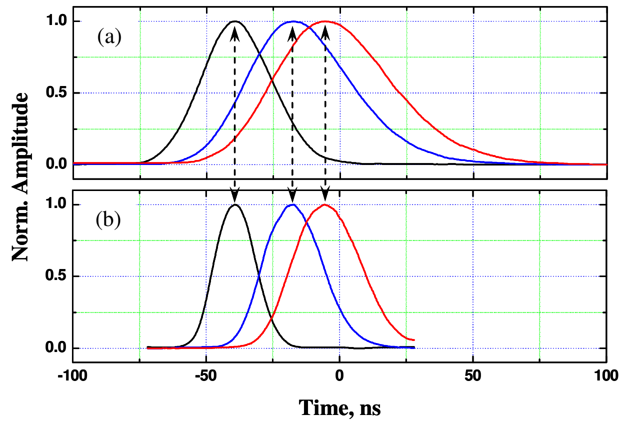

Fig. 3. (a) Normalized waveforms of pulses that experienced time delays through SBS slow light and (b) normalized waveforms of transmitted pulses through a saturable absorber, showing noticeable pulse compression.

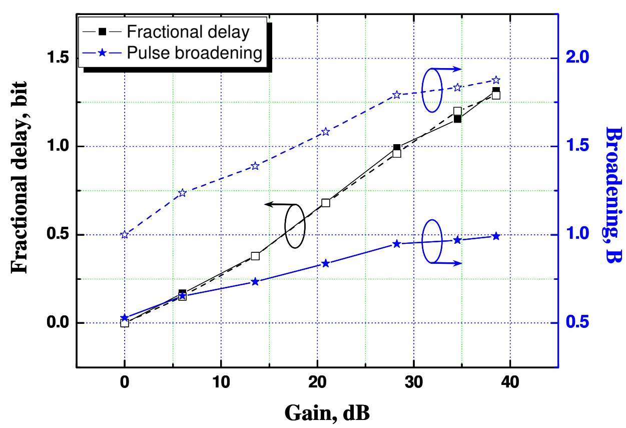

Fig. 4. Factional delays and broadening factors of signal pulses, respectively, with square and star symbols as a function of signal gain when the nonlinear loop mirror is present (filled symbols) or absent (opened symbols).

4. Conclusions

We have experimentally demonstrated a novel configuration to realize a SBS slow light delay line with essentially no pulse broadening. The inevitable pulse broadening in the SBS slow light medium was completely compensated after transmission through a nonlinear optical loop mirror. Experimental results showed 1.3-bit delays with actually no broadening. It must be noticed that any other type of fast saturable absorber can replace the nonlinear optical loop mirror. As a second advantage, this setup eliminated the background noise of the signal pulse, which is introduced by all the amplifiers of the system. We estimate that there is no practical limitation to cascade the system to achieve large fractional time delays without any broadening effect, and that the bandwidth of the delay line can be enlarged as well (by SBS pump spectral broadening). In the context of extending this setup to higher data rates, the

NOLM should provide a large flexibility since the response is instantaneous. With this simple implementation we have illustrated that nonlinear systems can be a very attractive solution to solve issues related to signal distortion in slow light systems. We are confident that other more sophisticated combinations of linear and nonlinear solutions can bring an even better response to compensate signal distortion in digital communication systems. However, this idea cannot be used for analog communication systems since the shape of the signal is not preserved and a strong harmonic distortion would appear.

Acknowledgements

We acknowledge the support from the Swiss National Science Foundation through project 200020-121860, the support from the European Union FP7 project GOSPEL and the Spanish Ministry of Education and Science through project TEC2006-09990-C02-02 and the fruitful environment of the COST Action 299 "FIDES".

#116964 - $15.00 USD Received 9 Sep 2009; revised 26 Oct 2009; accepted 30 Oct 2009; published 16 Nov 2009