Complete broadening compensation in a slow light system using a non-linear regeneration element

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Abstract: We demonstrate experimentally a new configuration to realize zero-broadening slow light. The inevitable pulse broadening in the slow light medium was completely compensated by a nonlinear regeneration element. Experimental results show 1.3-bit delays without distortion.

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

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. In recent years, a number of slow light systems have been experimentally realized based on different physical phenomena in optical media, such as coherent population oscillations, optical parametric amplification, stimulated scattering processes, etc [1]. 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 distortion that mostly manifests as pulse broadening. In order to overcome this limitation, several studies have demonstrated that tailoring the spectral properties of the medium could reduce data degradation while keeping the fractional delay [2-8]. This approach, however, is limited to delays of a few pulse durations, and therefore, a general scheme to achieve slow light without distortion for any arbitrary fractional delay is still under investigation.

In this paper, we propose and experimentally demonstrate a new configuration to compensate the inherent pulse broadening that is observed in slow light systems. 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 SBS slow light system and a nonlinear f loop mirror as the broadening compensation element, which plays a 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 fiber loop mirror, where it experiences a compression as a result of the nonlinear transmission. We effectively achieved 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 little distortion.

2. Principle and experimental setup

The experimental scheme that we use is depicted in Figure 1. It 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 experiences distortion. In the configuration we use, 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. In this way, the system can be tuned to have effectively no broadening at the output of the loop for large delay in the SBS delay line. 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 loop to match the states of polarization (SOP) 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 signal is split by a directional coupler into two counter-propagating electric fields, as shown in Figure 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 opposite direction, the optical path is identical to both propagating fields, resulting in the same linear phase shifts. As a result, the input signal is totally reflected into the input port. Therefore,

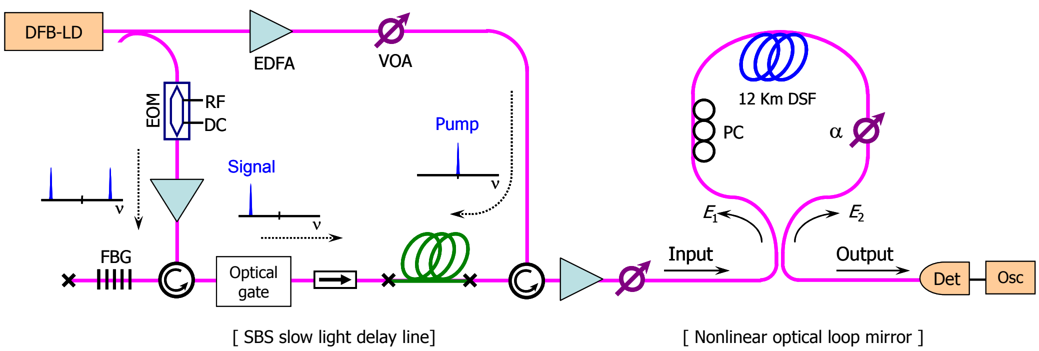

Figure.1: Schematic diagram of the experimental setup to produce non-broadening pulse delays. E1 and E2 present clock and counter-clock wise electric fields of pulses, respectively. EDFA; erbium-doped fiber amplifier, EOM; electro-optic modulator, FBG; fiber Bragg grating, DSF; dispersion shifted fiber and PC; polarization controller.

for 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, with a doubled impact for the wave propagating in the opposite direction. 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 signals. 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 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 this circumstance, the electric fields after a single pass via the loop are given by the expressions:

$$E_1' = \sqrt{\alpha / 2} A_{in} \exp[i \frac{1}{2} \varphi] \quad \text{and} \quad E_2' = i\sqrt{\alpha / 2} A_{in} \exp[i \frac{\alpha}{2} \varphi]$$

where A_{in} presents the amplitude of the input light and α is the attenuation factor for the E_2. The nonlinear phase shift φ is defined as $\varphi = \gamma P_o L$ where γ is the nonlinear coefficient, P_o is the optical power of the light at the input port and L is the fiber length. Therefore, the transmission coefficient T can be written as:

$$T = \frac{\alpha}{2}\left[1 - \cos\left(\frac{1-\alpha}{2}\right)\varphi\right] \simeq \frac{\alpha(1-\alpha)^2}{16}\varphi^2 \quad \text{for} \quad \varphi \ll 1$$

and the system turns out to be equivalent to a saturable absorber: the transmission grows for higher input powers, with a quadratic 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.

3. Experiments and results

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 a 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 at the Brillouin frequency shift so as to generate two first-order sidebands. The DC bias of the modulator was adequately set, so as to suppress the carrier. Therefore, only two sidebands were present at the output of the modulator. The lower-frequency sideband was then filtered by a fiber Bragg grating and launched into another external modulator to generate the signal pulse train. Consequently, a signal pulse train at the Brillouin frequency shift from the pump was generated. The pulses showed 27 ns FWHM duration at a repetition rate of 200 kHz.

The pulse train was sent into the SBS delay line while the pump power was increased from 0 to 30 mW. Figure 2a shows the normalized time waveforms of the signal pulses at the output of the Brillouin delay line. As in any typical Brillouin slow light system, the pulse exiting from the delay line was temporally both delayed and broadened with respect to the pump power. After passing through the delay line, the delayed pulse was amplified using another EDFA and launched into the nonlinear loop. In practice, the NOLM acts as a saturable absorber as previously described, so that the broadened pulses are sharpened at the output. Moreover, the unwanted background components in the pulse train, (mainly amplified spontaneous emission from the EDFAs and the Brillouin amplifier),

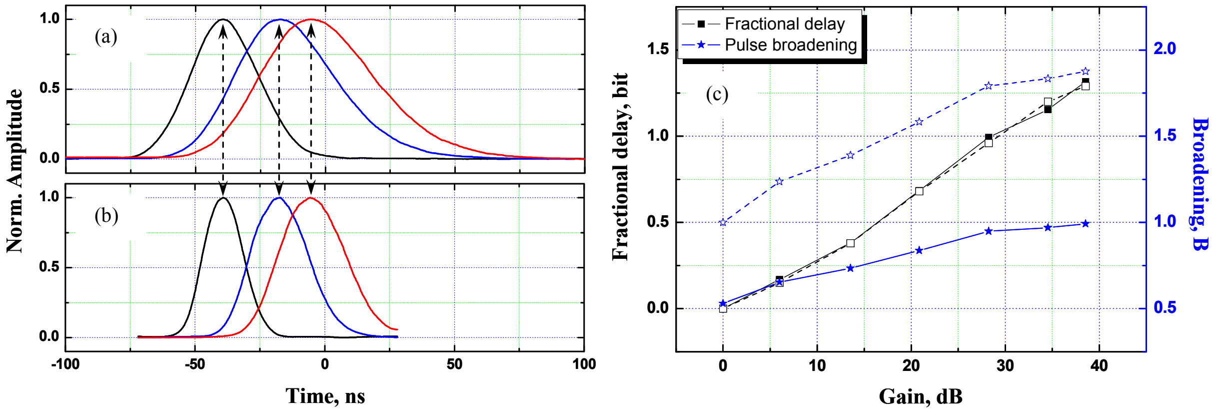

Figure.2: (a) Normalized waveforms of delayed pulses through SBS slow light and (b) normalized waveforms of transmitted pulses through a saturable absorber, showing noticeable pulse compression. (c) Factional delay and pulse broadening with square and star symbols, respectively when the nonlinear loop mirror is present (filled symbols) or absent (opened symbols).

were rejected. As shown in Figure 2b, the output pulse is compressed at the output of the loop, nevertheless fully preserving the time delays achieved in the SBS delay line. Figure 2c shows the measured fractional delay and pulse broadening as a function of signal gain. The system allows producing fractional delays of up to 1.3-bits (equivalent to 36 ns delay) without any broadening. This result is fully consistent with the prediction for a transmission depending quadratically on the intensity, which gives a compression by a factor $\sqrt{2}$ when applied to a Gaussian pulse. 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 takes into account the signal-to-noise ratio of the setup. We observed that the output pulse 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.

4. Conclusions

We have demonstrated experimentally 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 in a nonlinear optical loop mirror. Experimental results showed 1.3-bit delays with effectively no broadening. It must be noticed that any other type of fast saturable absorber can replace the nonlinear mirror. As a second advantage, our setup allowed to eliminate the background noise 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 with no broadening, or to increase the bandwidth of the delay line. With this simple implementation we want to show that nonlinear systems can bring a very attractive solution to solve the issue related to distortions in slow light systems. We are confident that other more sophisticated nonlinear solutions can bring an even better response to compensate distortions.

We acknowledge the support from the Swiss National Science Foundation through project 200020_121860, the Spanish Ministry of Education and Science project TEC2006-09990-C02-02 and the European Community's Seventh Framework Programme [FP7/2007-2013] under grant agreement n° 219299 (GOSPEL project).

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