Minimizing distortion and enlarging group delay in Brillouin slow light systems by gain profile optimization

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Abstract: Optimal gain spectra minimizing distortion and enhancing delaying efficiency in linear slow light systems are predicted and experimentally validated by shaping the gain spectral profile in a Brillouin fiber amplifier.

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1. Introduction

Controlling the speed of light in optical media has turned into one of the most promising fields during the past few years owing to its interesting potential applications as all-optical variable delay lines, light-matter interaction enhancement and signal processing [1]. Several slow light approaches have been demonstrated through the generation of high normal dispersion in sharp spectral resonances based on different physical interactions [1]. However, a limit to the maximum time delay always exists since amplitude and phase distortions can never mutually compensate in linear slow light systems and large delays are inevitably subject to major distortion [2].

In this paper, a strategy to minimize pulse distortion for a given delay is proposed and experimentally validated in a stimulated Brillouin scattering (SBS) slow light system. Considering a real limited gain bandwidth, a specific parabolic gain profile with symmetric sharp cutting edges turns out to be optimal for minimizing pulse distortion and enhancing the delay efficiency, rather than the flat-top gain profile, particularly for large fractional delays.

2. Theoretical background and simulation results

Like any linear slow light system, SBS-based slow light in optical fibers is inherently affected by distortion [1-3], resulting from the frequency-dependent Brillouin gain and nonlinear phase response. Compared to other methods [1], SBS offers interesting advantages, such as the possibility to arbitrary change the bandwidth and spectral shape of the gain medium [3,4], giving some freedom to minimize distortion and maximize delay efficiency. Unfortunately, these two conditions are widely incompatible, leading to the known tradeoff between delay and distortion [2].

In general, the root-mean-square (RMS) pulse width at the output of the system can be expressed as [2]:

$$\sigma_t^2 = \sigma_X^2 + \sigma_\varphi^2 = \frac{1}{E_\omega}\int_{-\infty}^{+\infty}\left|\frac{dX(\omega)}{d\omega}\right|^2 d\omega + \frac{1}{E_\omega}\int_{-\infty}^{+\infty}|X(\omega)|^2\left|\frac{d\varphi(\omega)}{d\omega}\right|^2 d\omega \ , \tag{1}$$

where the first (σ_X) and second (σ_φ) terms are the amplitude and phase contributions, respectively. $X(\omega)$ is the amplitude distribution and $\varphi(\omega)$ the phase distribution of the output pulse spectrum, which is the input pulse spectrum multiplied by the transfer function of the gain process. E_ω is the total energy of the pulse.

The slow light effect is predominantly driven by the limited bandwidth and the curvature of the gain profile, both being generically described by the simplified distribution $g(\omega) = \left[g_0 - g_2(\omega/\Omega)^2 + O(\omega^4)\right]\cdot\Pi\left(\omega/(\Omega/2)\right)$ for a gain window of strictly limited bandwidth Ω. g_0 is the peak gain (in linear amplitude scale), g_2 is the *gain profile index* defining the spectral curvature, which takes *positive* values for slowing light effects (note the negative sign in front of g_2), $\Pi(\cdot)$ is the rectangular function, and $O(\omega^4)$ represents higher-order terms which turn out to have a very moderate impact in practical cases. For a Gaussian-shaped input pulse, the amplitude, phase and total broadenings can be evaluated using Eq. (1) [2]. Fig. 1(a) shows the pulse broadening normalized to the input RMS pulse width (σ_{in}) as a function of the gain profile index g_2, for pulses of 880 ps delayed in a SBS slow light medium of 32 dB gain and 1 GHz bandwidth. It can be observed that the amplitude distortion induced by the slow light system increases as g_2 increases from 0 to 1, whilst the phase broadening exhibits a minimum at $g_2 = 0.5$. Note that, although no amplitude distortion ($\sigma_X/\sigma_{in} = 1$) is expected for a flat-top gain profile ($g_2 = 0$) [4], a significant broadening can still be obtained due to the dominant high levels of phase distortion ($\sigma_\varphi/\sigma_{in}$). On the other hand, when $g_2 > \sim 0.4$, the contribution of the amplitude distortion turns out to be dominant. In consequence, a minimum total distortion can be found for an intermediate value of g_2, which in this case is close to 0.25.

Fig. 1(b) shows the linear relation between the index g_2 and the fractional delay (defined as the group delay ϕ_l divided by the input pulse width τ_{in}). It can be observed that when g_2 increases, the fractional delay also increases as a result of the higher gain spectral curvature that reduces the effective full-width half-maximum gain bandwidth.
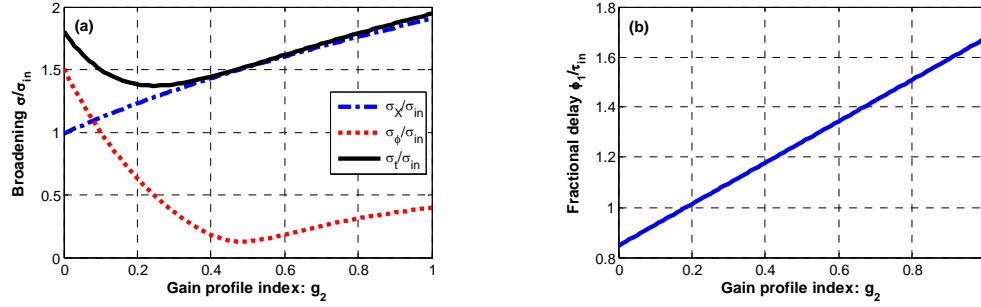

Fig. 1. (a) Pulse broadening (amplitude, phase and total contributions) and, (b) fractional delay as a function of the gain profile index g_2. The particular situation depicted here is for pulses of 880 ps and a 32 dB peak SBS gain of 1 GHz bandwidth.

3. Experimental setup

The experimental setup used to test these theoretical predictions is depicted in Fig. 2. The CW light from a distributed feedback (DFB) laser (λ=1551 nm) is divided into two branches by an optical coupler. The upper branch is used to generate the probe signal by using a Mach-Zehnder modulator (MZM) driven by a microwave source at a fixed frequency of 10.8 GHz (corresponding to the peak Brillouin gain frequency in the fiber). A tunable fiber Bragg grating (FBG) is used to select one of the probe modulation sidebands. 880 ps probe pulses showing high extinction ratio are obtained by fast-switching a semiconductor optical amplifier (SOA), and then amplified using an erbium-doped fiber amplifier (EDFA). A tunable optical filter (TOF) suppresses the EDFA out-of-band noise. The probe pulses are launched through an optical isolator into a 25 km standard single-mode fiber (SMF).
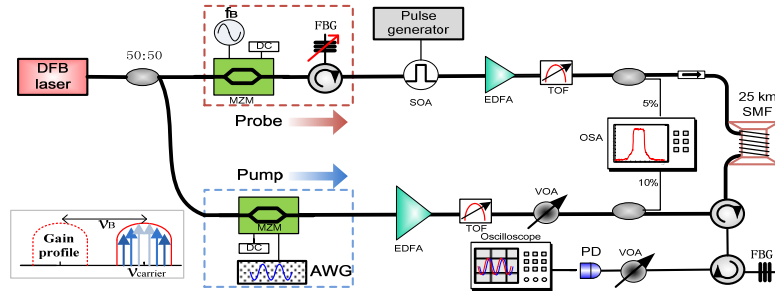

Fig. 2. Experimental setup for the measurement of fractional delay and pulse distortion using a gain-shaped SBS slow light medium.

Meanwhile, the light in the lower branch serves as the Brillouin pump wave and is modulated by a MZM operating in carrier-suppression mode using an arbitrary waveform generator (AWG). This way the optical spectrum of the pump can be precisely shaped through this external modulation with a frequency swept from 0 to 500 MHz and a repetition period of 2 μs (much smaller than the 125 μs propagation time along the 25 km SMF). Since both modulation sidebands are retained, a symmetric Brillouin gain spectrum spanning over 1 GHz bandwidth is obtained. The so-tailored pump is amplified by an EDFA, its peak power is controlled by a variable optical attenuator (VOA), and then 10% of the power is monitored by an optical spectrum analyzer (OSA). Finally, the pump light is launched into the fiber through a circulator and utilized to amplify and delay the probe pulses. A circulator and a narrowband FBG are employed in the receiver to filter out the Rayleigh light backscattered from the pump. Pulses are then detected by a 1 GHz photo-detector and a high-speed oscilloscope, after the adjustment of the peak power by a VOA.

4. Results and concluding discussion

Several gain profiles shaped under a generic quadratic form $g(\omega) = g_0 - g_2 \cdot (\omega / \Omega)^2$ over a strict 1 GHz bandwidth have been generated by programing the AWG. The amplitude and phase responses of the SBS slow light medium have been simultaneously measured using a vector network analyzer (VNA), whose output electrical signal is used to modulate the probe with a frequency spanning the range 8−12 GHz, whilst the output (response) of the system is launched to a 25 GHz detector connected to the input of the VNA. Fig. 3(a) shows that the flat-top gain profile (free from amplitude distortion) induces a strong phase distortion (highly non-linear phase response). The profile with $g_2 = 1$ in Fig. 3(c) introduces high amplitude distortion (strong low-pass effect) and moderate phase-distortion. The

intermediate case with g_2 = 0.5 (Fig. 3(b)) shows a nearly perfect non-distorting linear phase response while keeping a limited low-pass effect on the amplitude. This is in excellent agreement with the expected theoretical results above described in Fig. 1.
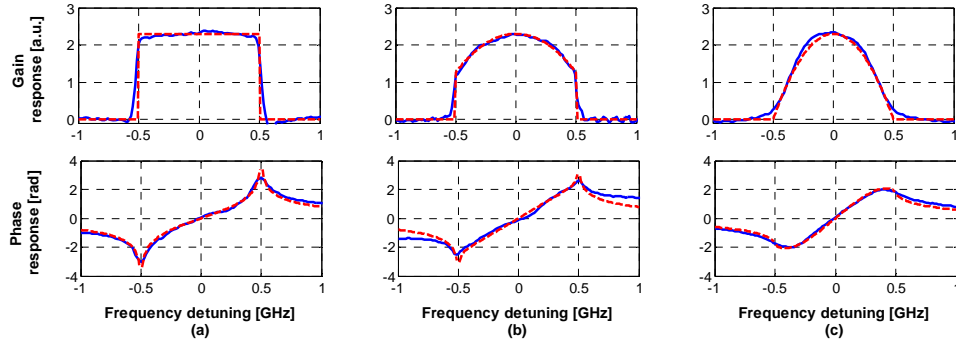

Fig. 3. Gain (top) and phase (bottom) response for three different gain profiles having 1 GHz bandwidth and 20 dB gain (g_0=2.3). (a) g_2 = 0; (b) g_2 = 0.5; (c) g_2 = 1. Blue solid lines: measured gain profile and phase response. Red dashed lines: theoretical curves.

Shaped gain profiles are utilized for slow light generation to delay 880 ps pulses using the setup shown in Fig. 2. Fig. 4(a) illustrates the time-domain waveforms of the delayed pulses for different gain profiles with 32 dB peak SBS gain. Enhanced delaying is found as expected by gradually changing the gain profile index g_2 from 0 up to 1. A maximum delay of 1.27 ns is observed when g_2 = 1, while the flat-top gain profile with g_2 = 0 provides the minimum delay of 0.79 ns, as expected from the theoretical analysis. A serious phase distortion can be found with indexes g_2 in the 0 to 0.25 range (evidenced by the second peak and long tails resulting from higher-order dispersion), whereas profiles with g_2 between 0.5 and 1 are dominated by amplitude distortion, showing a smooth low-pass filtering effect. These results fully agree with the theoretical predictions presented in Section 2.
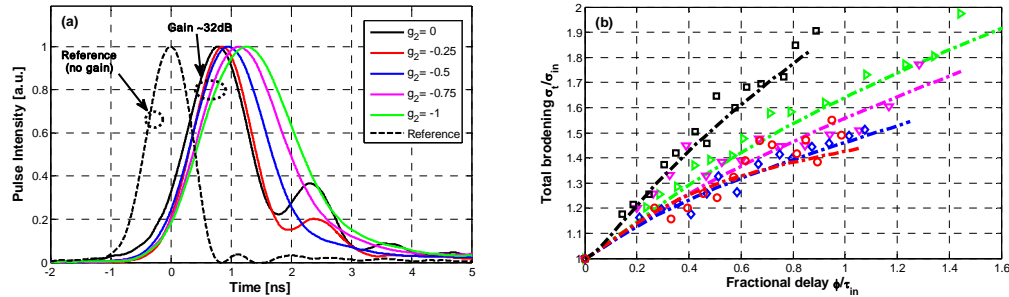

Fig. 4. (a) Normalized pulse waveforms of the reference with no gain (black dashed line) and of the delayed signals (colorful solid lines) for different gain profiles (with 32 dB gain). (b) Total broadening versus fractional delay (dots: experimental data; dashed lines: theoretical curves).

Finally, by calculating the RMS value of the delayed pulses, the experimental total broadening versus fractional delay is obtained for the different gain profiles, as depicted in Fig 4(b). This figure shows a good agreement between experiments (dots) and predictions (dashed lines), presented in Fig. 1 under the same conditions. Considering the tradeoff between amplitude-phase broadening and delaying power, optimal profiles are found for values of g_2 between 0.25 and 0.5. Actually Fig. 4(b) clearly demonstrates that the flat-top gain profile (black dots/line) is not a good choice due to its poor delaying efficiency and the strong phase distortion observed at large fractional delays.

Even though distortion is known to be intimately bound to the delaying effect in a linear slow light system, it is shown here that there is some space for optimization and parabolic gain profiles with a profile index g_2 between 0.25 and 0.5 are proved here to minimize the pulse distortion for all usual fractional delays.

5. References
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