Extended delay of broadband signals in stimulated Brillouin scattering slow light using synthesized pump chirp

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Abstract: Judicious chirping of a directly modulated pump laser is used to broaden the intrinsic linewidth of stimulated Brillouin scattering in an optical fiber. The modulation waveform is designed to obtain a spectrum with sharp edges, resulting in phase gradients stronger than those obtained for random pump modulation. The gain and phase frequency response of the slow light process are measured by a vector network analyzer, and the delays obtained for our tailored modulation are compared with the case of random direct modulation. For equal pump powers and gain bandwidths (FWHM), the tailored modulation waveform introduces 30-40\% longer delays. Using this technique, pseudo random bit sequences of 5 Gb/s were successfully delayed by up to 120 ps (BER<10^{-5}) and 80 ps (BER<10^{-9}).

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References and links

1. Introduction

Tunable optical delays, based on the ability to control the group velocity of signals propagating through an optical medium, have been at the focus of extensive research recently. Such tunable delays should prove important for applications such as clock alignment of optical communication signals, optical signal processing and microwave photonics [1-3]. Controllable delays may be achieved in the vicinity of gain or absorption peaks, introduced by a variety of non-linear mechanisms [1, 2], which are accompanied by large spectral gradients of the optical phase. These phase delay gradients modify the group velocity, which can be made slower than that of the linear medium [4, 5], and in some cases even faster [6]. These conditions are often referred to as "slow light" and "fast light", respectively. The group velocity of light was reduced by orders of magnitude using electromagnetically-induced transparency in cold atomic gas [4, 5], population oscillations in quantum well material [7], and photonic crystal structures [8].

Realizations of slow and fast light in optical fibers, operating at room temperature, are particularly attractive for optical communication and signal processing applications. Numerous physical mechanisms have been successfully utilized, including Stimulated Brillouin Scattering (SBS) [3, 9-11], Raman scattering [12], Raman-assisted parametric amplification [13] and a combination of four-wave mixing and dispersion [14]. For narrowband signals, SBS offers relatively long delays, robustness, implementation simplicity, and relatively low threshold power in standard fibers.

However, most applications of slow-light-based time delays would require a usable bandwidth of several GHz, compatible with the data rates of current optical communication systems. While early demonstrations of SBS-induced slow light used a continuous wave (CW) pump laser to obtain only 30MHz-wide SBS gain curve [3, 9-11, 15], recently this spectral width was successfully broadened through modulation of the pump laser [3, 16-18], culminating in the delay of a single 75ps pulse by 47 ps [19]. The pump modulation can be either external [3, 17, 18], or direct [16, 19], where a relatively narrowband amplitude modulation of the injection current gives rise to frequency chirp in the laser output [20].

increased bandwidth is achieved at the expense of a higher pump power and reduced delay [21, 22]. In addition, when the signal bandwidth approaches the spectral width of the SBS process gain curve, considerable distortion and pattern dependence may occur [15, 17, 19]. With available pump power often limited, careful trade-offs among delay, bandwidth and signal fidelity are essential [15, 17, 22].

Previously reported schemes for broadband SBS slow light had relied on stochastic direct modulation of the pump signal, using either a noise source [19], or a Pseudo-Random Bit Sequence (PRBS) [16]. Although a large bandwidth has been achieved, it is tempting to examine the role played by the waveform of the modulating pump current on the SBS process. It was previously shown theoretically that a judicious choice of the spectral line shape of the SBS gain could lead to better performance [22]. In this paper, we use both current-induced and thermally-induced chirp, [23, 24], to tailor the optical pump spectrum of a semiconductor laser using a combination of a deterministic, periodic current modulation together with a small random component. The optical spectrum of the pump laser is synthesized to a specific shape, using a previously established model of chirp dynamics [23, 24]. Adjustment of the modulating waveform provides extra degrees of freedom for control of the gain and phase response of the SBS process. The gain and phase response of broadband SBS are measured experimentally, using different pump modulation parameters. We show that when compared with random noise pump modulation, a properly chosen periodic waveform increases the group delay by 30-40%, for the same pump power and gain bandwidth. The broadened SBS process was successfully applied in delaying 270 ps wide isolated pulses and 5 Gb/s Non-Return to Zero (NRZ) patterns. Using this novel technique, PRBS data of 5 Gb/s were successfully delayed by up to 120 ps with a BER<10^{-5}, a result we could not obtain using random pump modulation of equal bandwidth and optical power.

The rest of this paper is organized as follows: Section 2 briefly describes the chirp dynamics of a Distributed Feed-Back (DFB) laser, and the synthesis of the optical spectrum of the modulated pump laser. Measurements of the gain and phase response of broadband SBS are reported in Section 3, and the corresponding delay of pulses and PRBS signals is detailed in Section 4. Finally, a discussion of the results and future work is given in Section 5.

2. Optical spectrum of directly modulated DFB lasers.

Direct modulation of the injection current of a DFB laser affects its instantaneous optical frequency through three separate mechanisms: transient, adiabatic and thermal chirp [20, 25]. Transient chirp is associated with the mutual feedback of photon and carrier densities, following a step transition of the current [26]. The typical time constants are of the order of 100 ps, so that transient chirp may be neglected for direct modulation at MHz rates, to be used below. Adiabatic chirp describes the frequency variations introduced by the current-related changes of the equilibrium carrier density. The adiabatic chirp contribution immediately follows the instantaneous injection current, with a magnitude in the range of 0.1-1 GHz/mA [20, 23]. Thermal chirp is proportional to the instantaneous temperature of the laser active region, which modifies both its refractive index and physical length [25]. The thermal chirp is slower to evolve, and its dynamics are determined by the thermal conductivity and capacitance of the various structural layers. In a previous study [23, 24], a simplified, semi-empirical model for the thermal effect of the modulating current i(t) on the instantaneous optical frequency ν(t) was established through a convolution integral, in which its impulse response is characterized by a weighted series of time constants τ_n, n = {1...N}:

\[ ν(t) = i(t) ⊗ h(t); \quad h(t) = \sum_{n=1}^{N} Δν_n exp \left(-\frac{t}{τ_n}\right) \]

These time constants correspond to the thermal properties of different layers, and they range from tens of ns to several ms [25]. With prior knowledge of the adiabatic and thermal chirp parameters, the instantaneous optical frequency of a DFB laser subjected to arbitrary direct modulation can be determined, and the optical spectrum may be synthesized [24].
The search for a 'more slowing' modulation waveform is motivated by the observation that an SBS gain curve with steep edges will give rise to longer delays. This observation can be demonstrated using the Kramers-Kronig relations [19, 22]:

\[
\text{Im}[g(\omega)/2] = \frac{2}{\pi} \int_0^\infty \frac{\text{Re}[g(\omega)]/2}{\omega^2 - \omega' \omega} \, d\omega
\]

(2)

where \( g(\omega) \) is the complex gain function of the SBS process [3, 19]. Let us compare between two shapes of \( \text{Re}[g(\omega)] \), shown schematically in Fig. 1(a). Since the actual power gain seen by the signal to be delayed (the probe signal) depends exponentially on \( \text{Re}[g(\omega)] \), the two spectral shapes will result in similar bandwidths. However, the corresponding phase response curves, depicted in Fig. 1(b), show significant differences. It is the nature of the integral relation of Eq. (2) that transforms the abrupt edges of the dashed curve into the larger frequency gradient of the phase response, resulting in a longer delay. Previous works [16, 19] have related the SBS complex gain function to a convolution of the pump spectrum and the 30 MHz-wide natural Lorentian of the SBS process. Therefore, a pump spectrum synthesized to have sharp edges would produce a complex SBS gain function with longer delays.

Following the discussion of the last paragraph and using our model for the laser chirp, we found that a periodic modulation waveform of the form:

\[
i(t) = i_0 + \Delta i \left[ 1 - \left( \frac{t \mod T}{T} \right)^{1.5} \right],
\]

(3)

with a period \( T = 320\text{ns} \) and magnitude \( \Delta i = 24\text{mA} \) would give rise to a broadened pump spectrum of the required shape (64 samples were chosen for each period, which for our 200 MSamples/s arbitrary waveform generator resulted in a period of \( T = 320\text{ns} \). Longer periods did not affect the results). The laser bias current \( i_0 \) was 80m. Figure 2(a) shows the simulated result together with a measured spectrum. This spectral measurement was performed by beating the modulated laser with a CW laser on a photodiode, whose output fed a Radio Frequency (RF) spectrum analyzer [16]. The measured optical spectrum is in good agreement with the simulated predictions, and the design objective of sharp spectral transitions is met, albeit with sizable fast transients. Smoothing of these disturbing spectral features was achieved by adding a random modulation component of Gaussian statistics. The measured optical spectrum is shown in the dashed line of Fig. 2(b). Also shown is the spectrum for entirely random modulation (solid), with a bandwidth of 200 MHz and RMS magnitude of...
20mA. Both modulation schemes of Fig. 2(b) were alternately used to drive the pump laser in the broadband SBS slow light experimental setup, to be described next.

![Graph a](image1)

![Graph b](image2)

Fig. 2. (a): Dashed line: simulated optical spectrum of DFB laser periodically modulated by the waveform of Eq. (3) with the following parameters: adiabatic chirp coefficient $0.33 \text{ GHz/mA}$, $\tau_{1,2} = 20, 200 \text{ ns}$ and $\Delta \nu_{1,2} = 0.15, 0.48 \text{ GHz/mA}$ [22]; Solid line: corresponding measured spectrum. (b): Dashed line: measured optical spectrum for a directly modulated DFB laser, using the waveform of Eq. (3) together with a 20 MHz random component of 2mA (rms); Solid line: measured optical spectrum for a directly modulated DFB laser, using 200 MHz random modulation of 20mA (rms).

### 3. Gain and phase response of SBS with directly modulated pump

Figure 3 shows the setup for characterizing the optical gain and phase response of the SBS process. The laser of the previous section was used to generate the pump signal. The pump laser signal was directly modulated by the output voltage of an arbitrary waveform generator, and amplified by a high power optical amplifier. A circulator directed the pump signal into 20 km of Dispersion Shifted Fiber (DSF), which was used as the SBS non-linear medium. A stable tunable laser was used as a probe signal source, and a polarization controller adjusted the state of polarization of the probe signal for maximum interaction [19, 27]. The probe laser was connected to a Single Side-Band (SSB) LiNbO$_3$ Mach-Zehnder modulator. Using a Vector Network Analyzer (VNA), the upshifted modulation sideband scanned the broadened SBS gain curve over a 2-15GHz range, while the frequency of the probe laser was tuned to fall below this curve. The VNA detected the beating signal of the carrier and sideband, and its magnitude and phase as a function of frequency with the pump turned off were taken as reference values. The changes to the beating signal with the pump laser turned on are, therefore, proportional to the complex response of the SBS process [17, 27].

![Diagram](image3)

Fig. 3. Setup for the measurements of the SBS slow light gain and phase response. BPF: bandpass filter. EDFA: Erbium-doped fiber amplifier.
Examples of the SBS power gain curves obtained for synthesized and random direct pump modulation are shown in Fig. 4(a-b), using pump power levels of 19-22 dBm. The Full Width at Half Maximum (FWHM) of the gain curves are approximately 3 GHz for both modulation formats. The corresponding phase response curves are displayed in Fig. 4(c-d). As anticipated, the steep spectral transitions of the gain curve observed for the tailored modulation are accompanied by stronger gradients of the phase response. The response also shows a phase delay offset, which does not affect the group delay. The calculated group delays $\tau$, determined by the slope of a linear fit to the phase response within the FWHM of the gain curve, are shown in Fig. 5 as a function of the maximum SBS power gain. For equal maximum gain of the probe signal, the calculated group delay obtained with synthesized modulation is 30-40% longer.

Fig. 4. Measured gain curves of SBS using synthesized (a) and random (b) direct pump modulation. The pump power levels are (top to bottom): 22 dBm, 21 dBm, 20 dBm, 19 dBm. Measured phase response curves of SBS using synthesized (c) and random (d) direct pump modulation. The pump power levels are: 22 dBm (blue), 21 dBm (green), 20 dBm (red).

Fig. 5. Calculated group delays as a function of maximum SBS power gain, using synthesized (asterisk signs) and random (plus signs) direct pump modulation.
4. Delay of broadband pulses and PRBS data.

The broadened SBS process was used to delay short pulses and high rate PRBS signals. The output of the probe tunable laser was connected to a LiNbO₃ Mach-Zehnder modulator, driven by a PRBS generator. The delayed, amplified signal at the DSF output was detected by a sampling oscilloscope. In the first set of measurements, isolated pulses with a FWHM of 270 ps were used. Figure 6(a) shows the normalized output pulses for synthesized pump modulation and pump power levels of 18 and 22 dBm, alongside the original pulse. Also shown are the calculated output pulses, based on the gain and phase response measured by the VNA. The delay and broadening of the pulses are well accounted for by the complex SBS response [17], with some differences at the tails of the pulse for 22 dBm pump power.

In the second part of the experiment, the probe pulses were replaced by 5 Gb/s, 2³¹-1 long NRZ PRBS. The output eye diagrams were observed, and the signal gain and delay were measured for both pump modulation formats and different pump power levels. Figure 6(b) shows the measured delay as a function of probe signal gain. The delays observed for synthesized modulation are longer by 30-40%, in agreement with the SBS phase response measurements of the previous section.

![a:](image1.png) ![b:](image2.png)

**Fig. 6.** (a): SBS induced delays of 270 ps pulses using synthesized pump modulation. Solid lines, left to right: input pulse, output pulse for pump power of 18 dBm, output pulse for pump power of 22 dBm. Dashed lines: calculated output pulses for pump power of 18 dBm (left) and 22 dBm (right). (b): Measured delays of 5 Gb/s NRZ PRBS as a function of power gain, using synthesized (asterisk signs) and random (plus signs) direct modulations.

An example of the output eye diagram, delayed by 120 ps using synthesized pump modulation, is given in Fig. 7. The BER for delays of 80, 100 and 120 ps using synthesized modulation were < 10⁻⁹, 10⁻⁸ and 4·10⁻⁶, respectively. The product of error free delay and bit rate was 0.4, achieved with pump power of 20 dBm. This is a novel demonstration of high bit rate, error free SBS-induced delay.

![Fig. 7. Output eye diagram of a 5 Gb/s NRZ PRBS, delayed by 120 ps using SBS with synthesized, direct pump modulation.](image3.png)
5. Summary

In summary, the delay obtained in broadband SBS slow light in fiber was extended using direct modulation of the pump laser with pre-designed chirp. Manipulating the modulation waveform provides extra degrees of freedom for adjustment of the SBS gain and phase response. The chosen modulation waveform generates a tailored pump spectrum with sharp spectral edges, leading to stronger gradients in the SBS phase response. A delay extension of 30-40% was observed, when the novel, synthesized modulation had replaced random direct modulation of equal FWHM bandwidth and pump power. Using this novel technique, PRBS data of 5 Gb/s were successfully delayed by up to 120 ps with a BER<10^-5. While the obtained extended delay is still only a fraction of a bit period, it may prove useful in data synchronization and microwave photonics.

A more comprehensive study is under way to theoretically evaluate the relation between the spectrum of a broadband, non-stationary pump and the optical phase response of the probe signal, including pump depletion, aiming at optimizing the modulation waveform.

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