Progress on Stopped Light and Large-Delay Slow Light in Optical Fibers

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Abstract: Recently, slow light was achieved in room temperature optical waveguides, which is accelerating the transition of this technique to applications. This paper reviews recent progress in obtaining large optically-controllable slow-light delays.

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1. Introduction

Over the last decade, there has been great progress in devising methods for tailoring the dispersion of optical materials, such as electromagnetically induced transparency, photonic crystals, and nano-optic resonators [1]. By tailoring the dispersion using all-optical methods, it is possible to adjust the group velocity υ_g of a pulse. Large normal dispersion, where the refractive index of the material increases with frequency over some range, results in slow light, where the group index n_g is greater than one and υ_g is less than the speed of light in vacuum. Slow light has potential applications for optical buffering, data synchronization, optical memories, and optical signal processing.

Most slow light techniques rely on resonant effects that cause large normal dispersion in a narrow spectral region (approximately equal to the resonance width), as shown in Fig. 1. Much of the early slow-light research was conducted with near an atomic resonance in a gas of atoms, where large changes in n_g where obtained by creating large optical coherence in the gas. More recently, it has been shown that simulated scattering process (such as stimulated Brillouin scattering (SBS) [2, 3]) in laser-pumped optical waveguides gives rise to slow light at any wavelength where the material is transparent. This research has attracted considerable interest due to the inherent advantages of optical waveguides, such as compatibility with fiber-optic communication systems, room temperature operation, and the potential for large bandwidths.

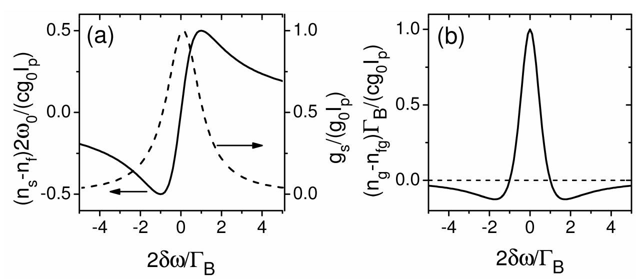

Fig. 1 Slow light in an optical fiber due to stimulated Brillouin scattering. (a) The Stokes amplification resonance of width $2\Gamma_B$ (dashed line) and the associated change in refractive index (solid line). (b) Large normal dispersion near the center of the line shown in panel (a) gives rise to a positive group index (slow light) at line center. From Ref. [4].

2. Minimizing Pulse Distortion

In the applications described above, the primary requirements for slow-light pulse delay are that the temporal pulse delay is large relative to the pulse width and that the pulse is not substantially distorted. These two requirements largely oppose each other, with large delay often coming at the cost of greater distortion for fixed experimental resources. This tradeoff has been studied in systems described by simple Lorentzian resonances [5-7], for example, where it is found that it is possible to obtain large delays, but the gain (or absorption) of the system has to be increased. For systems based on a gain resonance, such as SBS, the attainable gain is limited by the occurrence of self-oscillation, thereby limiting the attainable delay in a single slow-light delay line. Self-oscillation can be suppressed using multiple delay lines separated by attenuators [8], but this increases the complexity of the system.

Another approach for decreasing distortion is to tailor the shape of the resonance giving rise to the slow-light effect. The SBS process lends itself naturally to distortion management because the amplifying resonance is directly related to the spectrum of the laser light pumping the Brillouin process. Using two [9,10], three [11-13], or more [14-16] closely spaced pump frequencies, it is possible to minimize the effects of higher-order dispersion on the delayed pulses. For example, Stenner *et al.* [9] introduced a general distortion metric and used it to show that optimizing over a larger number of physical variables can increase the distortion-constrained delay. They demonstrated this concept by comparing the optimum slow-light pulse delay achievable using a single Lorentzian gain line with that achievable using a pair of closely-spaced gain lines. They demonstrated that distortion management using a gain doublet can provide approximately a factor of 2 increase in slow-light pulse delay as compared with the optimum single-line delay, and improved the delay at the optimum bandwidth by a factor of approximately 8.

More recent work has focused on adjusting system parameter to optimize the eye-opening [12,13]. In one experiment, Shi *et al*. [13] have used a triple-gain-line composite resonance to obtain a slow-light delay of two pulse widths while keeping the eye-opening penalty below 1.87 dB, corresponding to a bit-error-rate of below 10^{-12}. Other work has shown that different data formats, such as differential-phase-shift-keying, can also reduce slow-light induced distortion [17].

3. Broad-band Slow Light

The bandwidth over which the slow-light effect occurs is approximately given by the width of the SBS resonance; thus, the data rate of signals passing through the slow-light medium is also limited to approximately the resonance width. In standard single-mode fiber, the SBS linewidth is of the order of 30 MHz, thereby supporting data rates only ~30 Mbits/s. For a slow-light delay line to be useful in current systems, it needs to operate at 10 Gbits/s or above. Recently, Herráez *et al*. [18] demonstrated that the SBS linewidth can be broadened by increasing the spectrum of the pump laser beam. For telecommunication lasers, it is easy to broaden their spectrum by summing the laser injection current with a random noise current. In this way, they achieved a SBS linewdith of ~325 MHz and delayed a 2.7-ns-long pulse by more than a pulse width.

Taking this a step further, Zhu *et al*. [19] have increased the SBS bandwidth to ~12 GHz and studied the propagation of a 10 Gbit/s data stream through the slow-light delay line. Figure 2a shows the broadened Stokes gain line, where it is seen that it is beginning to overlap with the anti-Stokes absorption resonance, indicating that the linewidth is comparable to the Brillouin frequency shift. Figure 2b shows the delay of a 75-ps-long pulse through this slow-light material, implying that 10 Gbit/s data can be slowed using this method. By using multiple broadened pump frequencies, it is possible to enhance the delay [20] and achieved bandwidths of ~ 25 GHz [21].

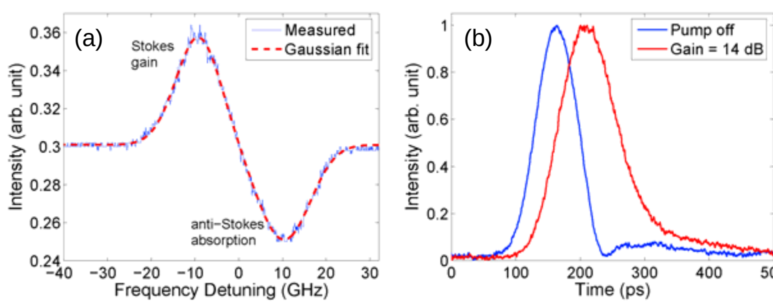

Fig. 2 Broadband slow-light. (a) Measured SBS gain spectrum with a dual Gaussian fit. The SBS gain bandwidth (FWHM) is found to be 12.6 GHz. (b) Pulse waveforms at 0-dB and 14-dB SBS gain demonstrating a delay of 47 ps. Adapted from Ref. [19].

4. Outlook

Over the past year, researchers studying slow light via stimulated Brillouin scattering have demonstrated that it is possible to minimize pulse distortion by tailoring the higher-order dispersion of the material, operate at data rates over 10 Gb/s using broad-band pump light, obtain controllable delays exceeding one pulse width, and delaying pulses with minimal change in the pulse amplitude. Larger relative delays appear possible by operating in the nonlinear regime, where the data pulses are intense enough saturate the SBS gain. I expect that methods for storing and stopping pulse, by converting them to acoustic disturbances, will appear in the near future. The general area of SBS slow-light is progressing at a fast pace and I look forward to seeing slow-light sub-assemblies integrated into functions telecommunication components.

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