Highly efficient Brillouin slow and fast light using As_2Se_3 chalcogenide fiber

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Abstract: We demonstrate the generation of slow and fast light based on stimulated Brillouin scattering in As_2Se_3 chalcogenide fiber with the best efficiency ever reported. The Brillouin gain of 43 dB is achieved with only 60-mW pump power in a 5-m single-mode chalcogenide fiber, which leads to the optical time delay of 37 ns with a 50-ns Gaussian pulse.

OCIS codes: (060.2310) Fiber optics; (060.4370) Nonlinear optics, fibers; (070.6020) Signal processing; (290.5900) Scattering, stimulated Brillouin; (350.5500) Propagation

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1. Introduction

The control of the group velocity of light is currently attracting much attention in the scientific communities because it has several significant applications such as optical buffers for all-optical routing, phased-array antennas, optical memories and optical signal processing [1-4]. While the electromagnetically-induced transparency (EIT) [2] or the coherent population oscillation (CPO) [3,4] has been used for slowing down the optical pulses in bulk-optic media and semiconductor devices, the slow light experiments in optical fibers were carried out via stimulated Brillouin scattering (SBS) [5-7], Raman scattering (SRS) [8] or Raman-assisted parametric amplification [9] with more flexibility and simpler configuration. These experiments make use of an optically-controlled narrowband gain or loss process occurring in the fiber, and the group velocity can be tuned continuously by simply controlling the pump power level. In particular the method based on stimulated Brillouin scattering has shown that it can reproduce almost all the experimental results achieved by the former studies such as slow light ($v_g \approx 71000$ km/s), faster-than-light (superluminal) propagation and even negative group velocities [10] with a simple bench top experimental setup at room temperatures. Additionally, recent experiments [11,12] have successfully demonstrated the arbitrary control of the operating bandwidth of SBS by proper frequency modulation of the pump wave, which has made it a more powerful tool for the generation of slow light. The method is expected to be applied not only for increasing the bandwidth but also for the designing and tailoring of the dispersion to minimize the inevitable pulse distortion in the delaying process.

From the practical point of view, the length of the delay fiber and the amount of pump power are key parameters which determine the amount of time delays. Considering the response time, the stability of the controlled delay and the onset of other nonlinear effects, previously reported figures [5,10] – several kilometer fiber with several tens of mW pump power or several meter with several watts – may not be practical in most applications. Besides, the enlargement of spectral bandwidth requires as much increase of the pump power in order to achieve the same amount of fractional delay [11]. All these aspects highlight the necessity of the efficiency enhancement in the slow light generation for more practicality. In a recent experiment, the use of a 2-m Bismuth-oxide highly nonlinear fiber (Bi-HNLF) was reported to generate 29-dB Brillouin gain and the resultant optical delay of 46 ns with 410-mW pump power [13]. As another experiments, it has been lately reported that a As_2Se_3 chalcogenide fiber can offer very high Brillouin amplification [14,15].

In this paper, we test the As_2Se_3 chalcogenide fiber to further improve the efficiency of the SBS-based slow light generation. The Brillouin gain of 43 dB is achieved in only 60-mW pump power in a 5-m chalcogenide fiber, which results in 37-ns optical delay of a probe pulse having 50-ns duration. We introduce a new figure of merit for the evaluation of optical fibers as a slow light medium including the consideration of the pump transit time, and the result shows the As_2Se_3 fiber is about 4 times more efficient than the Bi-HNLF. We believe this

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implementation shows that the chalcogenide fiber can be the best medium for the practical applications of the SBS slow light.

2. Principle

The process of SBS is the interaction of two counterpropagating waves, a strong pump wave and a weak probe wave. If a particular frequency relation is satisfied (i.e. $\nu_{pump}=\nu_{probe}+\nu_B$, ν_B being the Brillouin frequency), an acoustic wave is generated which scatters photons from the pump to the probe wave and the interference of these two optical waves in turn stimulates the process. Since the Brillouin gain bandwidth is as small as 30 MHz in conventional optical fibers, the SBS can be regarded as a narrowband amplification process, in which a strong pump wave produces a narrowband gain in a spectral region around $\nu_{pump}-\nu_B$ and a loss around $\nu_{pump}+\nu_B$. According to the Kramers-Kronig relation, a refractive index change is associated with the Brillouin gain/loss process and a substantial change of the group index $n_g=n+\omega\, dn/d\omega$ follows as a result of the sharp index transition, which leads to a controllable optical time delay.

The linear Brillouin gain along a fiber is expressed as $g_B L_{eff} P_{pump}/A_{eff}$, where g_B, L_{eff}, P_{pump} and A_{eff} are Brillouin gain coefficient, the effective length, the pump power and the effective mode area, respectively. The gain coefficient g_B depends on material properties as [16]

$$g_B = \frac{2\pi \cdot n^7 \cdot p_{12}^2}{c\lambda^2 \rho \cdot v_A \cdot \Delta\nu_B}, \qquad (1)$$

where n, p_{12}, c, λ, ρ, v_A and $\Delta\nu_B$ are the refractive index, the longitudinal elastooptic coefficient, the speed of light, the wavelength, the material density, the acoustic velocity and the Brillouin gain bandwidth, respectively. Recently, the g_B in a single-mode As_2Se_3 chalcogenide fiber has been measured to be ~ $6.08\text{x}10^{-9}$, more than 130 times larger than that of usual silica fibers, mainly as a result of its large refractive index of 2.81 [14].

For the slow light experiment, we use a 5-m single-mode As_2Se_3 fiber with a core diameter of 6 μm and a normalized frequency V of 2.17 at 1560-nm wavelength. The transmission loss is 0.84 dB/m which corresponds to an effective length of 3.2 m. The Brillouin frequency ν_B is measured to be 7.968 GHz at 1560nm and the reported value of the Brillouin gain bandwidth $\Delta\nu_B$ is about 13 MHz [14].

3. Experiments and results

The experimental configuration is shown in Fig. 1. A 1560-nm laser diode was used as a light source and the output power was divided by a 90/10 coupler. The 10% output was directly used as a Brillouin pump wave after being amplitude-controlled through an EDFA and a variable optical attenuator (VOA-1). The 90% output was launched into a phase modulator (PM) to create sidebands with a frequency difference around ν_B. The choice of the 90% coupler port for the probe is only to compensate the modulator extra loss and the incomplete modulation. A probe pulse train was generated by an intensity modulator (IM) and a pulse generator to have a Gaussian profile with a width (FWHM) of 50 ns at the repetition rate of 1 MHz. The amplitude of the probe pulse was controlled by an EDFA and a VOA (VOA-2).

The probe and the pump waves were launched into the 5-m As_2Se_3 fiber in counter-propagating direction using lensed fibers which showed a 1.8 dB coupling loss. The probe pulse from the fiber output was filtered by Fabry-Perot filter (F-P) and the time waveforms were recorded through a photodiode (PD) and an oscilloscope. In order to avoid the effect of gain saturation and any amplitude-dependent time biasing in the PD, we carefully controlled the amplitude of the initial probe pulse with the VOA-2 to keep the same probe power (~ 5 μW) on the PD regardless of the gain. The amount of the Brillouin gain could be calculated by the variation of the initial probe power which was monitored throughout the measurements.

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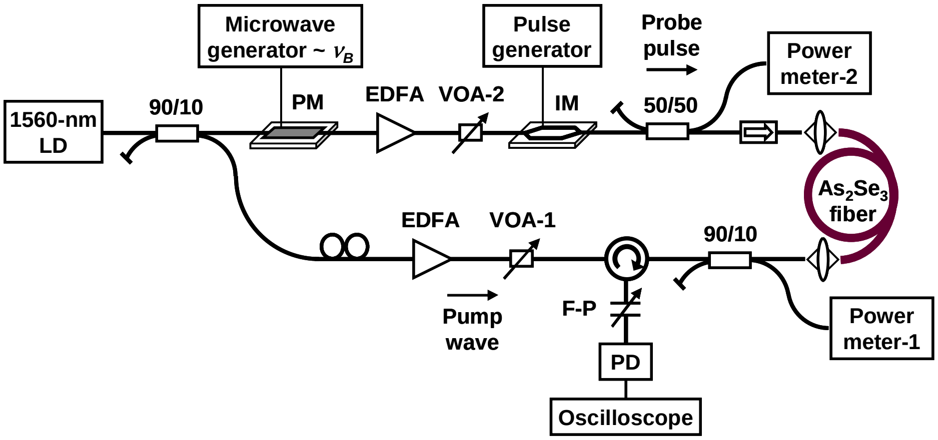

Fig. 1. Setup for optical delay experiment using a As_2Se_3 chalcogenide fiber: LD, laser diode; PM, phase modulator; EDFA, Er-doped fiber amplifier; IM, intensity modulator; VOA, variable optical attenuator; PD, photodiode; F-P: Fabry-Perot filter.

Figure 2 shows the measured time waveforms of the probe pulses for different Brillouin gain values ranging from -10 dB to 43 dB, where the pulse delay and advancement is clearly observed. The negative gain corresponds to the case of Brillouin loss which was measured using anti-Stokes sideband from the PM. The maximum gain value (43 dB) was limited by the noise coming from the spontaneous Brillouin emission of the pump.

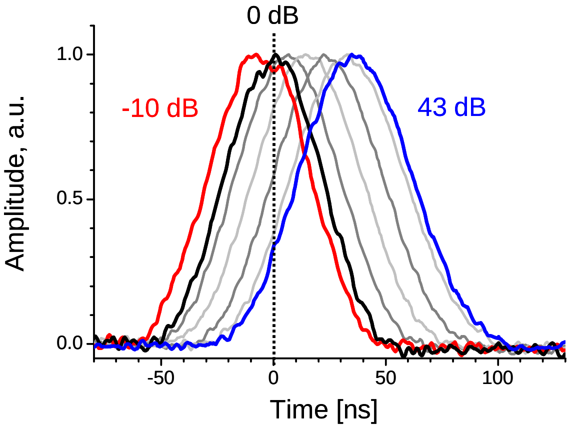

Fig. 2. Time waveforms of the probe pulses for different Brillouin gain. Note that the negative gain (-10 dB) corresponds to the case of Brillouin loss.

The measured Brillouin gain is shown in Fig. 3(a) as a function of the pump power which is linearly fitted with a slope of 0.71 dB/mW, and the time delay of the probe pulse is depicted in Fig. 3(b) as a function of Brillouin gain which is well fitted with a slope of 0.82 ns/dB.

In order to compare optical fibers as a SBS slow light medium, it is necessary to define a proper figure of merit for evaluation. Since the slope of the time delay versus Brillouin gain only depends on the inverse of the gain bandwidth and since this bandwidth can be arbitrarily extended in the broadband scheme by pump dithering [11], the gain coefficient is the only

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parameter that will scale the efficiency in the time delay generation. Another significant points are the response speed and the stability that will be inversely proportional to the refractive index of the fiber. Therefore, we can define the figure of merit (FOM) as follows:

$$FOM \equiv \frac{G}{P_{pump} \cdot L_{eff} \cdot n}, \tag{2}$$

where G is the Brillouin gain, P_{pump} the pump power, L_{eff} the fiber effective length and n the refractive index, respectively. The FOM of the As_2Se_3 fiber is calculated to be 0.079 dB/mW/m (0.71 dB/mW, 3.2 m, n=2.81), which is more than 4 times larger than the result of the Bi-HNLF (~ 0.019 dB/mW/m; 29 dB/410 mW, 1.67 m, n=2.22) [13] and 110 times better than observed in a conventional single-mode fiber (~ 0.00072 dB/mW/m; 21 dB/10 W, 2 m, n=1.45) [10]. It must be pointed out that these FOM's were all evaluated from data obtained in short fibers, so that the birefringence can be considered as uniform and the effect of random polarization change along the fiber can be fully neglected. In longer fibers they can be substantially reduced by the polarization mismatch resulting from a random birefringence.

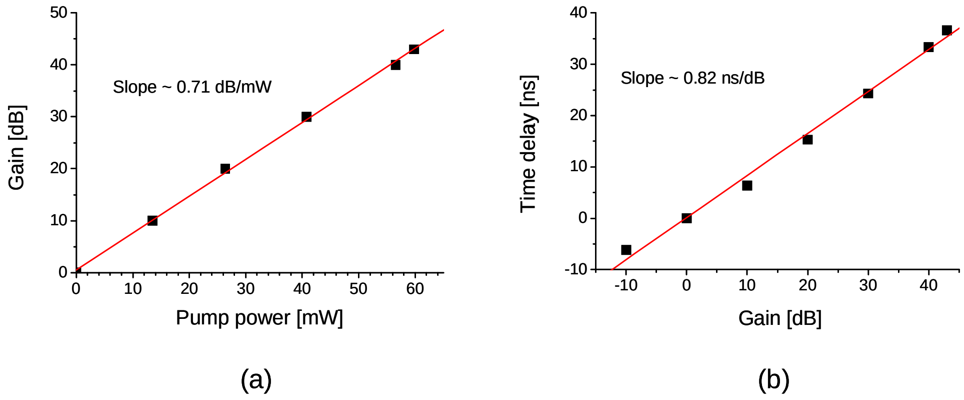

Fig. 3. (a) Amount of Brillouin gain as a function of the pump power in the 5-m As_2Se_3 fiber. (b) Time delay of the probe pulse as a function of Brillouin gain.

The variation of the pulse width (FWHM) as a function of gain is depicted in Fig. 4(a), where the 50-ns pulse was broadened about 16% in the 43 dB gain. The red curve is the fitting result based on the linear theory [17,18], in which the intrinsic linewidth is expected to be 54 MHz. We guess the large discrepancy between this result and the previously reported value (~ 13 MHz) might come from the irregularity of ν_B along the fiber. An inspection of the fiber core was carried out using an infrared video camera and the result showed large variation in the location of the core along the length, which could be as much as 30 µm from the center. This indicates that the uniformity of the fiber is yet far from ideal, and supports the idea that non-uniformities in the fiber core are responsible of this broadening. Additionally, taking into account that the core has a nominal size of 6 µm and the fact that the ratio of As/Se contents in the $As_{39}Se_{61}$ core may change slightly along the length, we believe that these discrepancies are expectable. We also think a future experiment using a shorter length of the fiber would be helpful for the confirmation of the origin.

Figure 4(b) shows the variation of the time delay and the gain of the probe pulse as a function of detuning frequency $\Delta\nu$ of the pump and the probe wave from ν_B. The maximum gain was set to 20 dB (at ν_B) and all the other parameters were fixed during the measurement. Due to the significant distortion of pulse waveforms, the half-maximum position of the front

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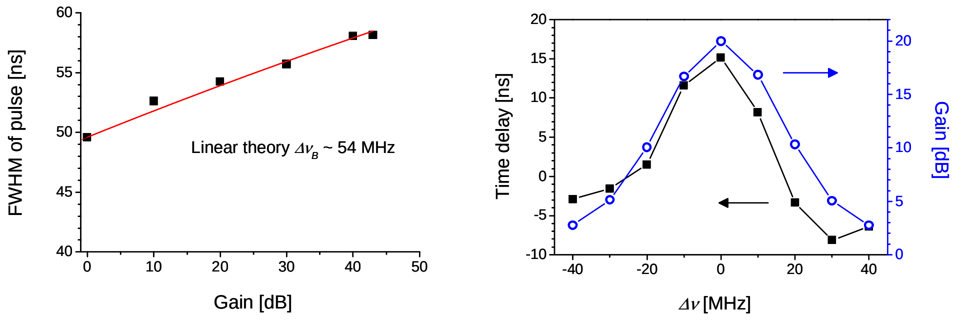
edge was used for the delay measurement. Both the time delay and the gain gradually decreased as the $\Delta\nu$ increased, which confirms that the SBS is the only origin of the slow light generation in this fiber. As formerly demonstrated in standard fibers [19], the gain-assisted advancement of the probe pulse was also observed for large $\Delta\nu$.



(a) (b)

Fig. 4. (a) Variation of the pulse width (FWHM) with respect to gain. (b) Variation of the time delay and the gain according to the detuning frequency ($\Delta\nu$) form ν_B (7.968 GHz). Note that the maximum gain was set to 20 dB and the pump power was not changed during the measurement.

4. Conclusion

We have demonstrated the highly efficient generation of the slow and fast light based on the SBS in a As_2Se_3 chalcogenide fiber. A Brillouin gain of 43 dB was achieved with only 60 mW pump power in a 5-m single-mode chalcogenide fiber, which leads to the optical time delay of 37 ns with a 50-ns Gaussian pulse. In terms of the proposed figure of merit, it shows 0.079 dB/mW/m which is about 4 times and 110 times more efficient than Bi-HNLF and conventional single-mode fibers, respectively. We hope this implementation improve the practicality of the SBS slow light with arbitrary bandwidth for future application.

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