Progress in the Slow and Fast Light based on Brillouin Scattering in Optical Fibers

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Abstract

Review on recent progress in the slow and fast light based on Brillouin scattering in optical fibers will be presented, where the brief history, the experimental results, and current research trends will be included.

Introduction

During the past few years, the research on the group-velocity control of optical pulses, i. e. slow and fast light (or slow light), in optical fibers has been among the hot issues in photonics societies as a promising technology for optical communication and sensor applications [1-27]. A number of valuable experimental results have been reported based on nonlinear optical processes such as stimulated Brillouin or Raman scattering (SBS or SRS), optical parametric amplification, soliton collision, coherent population oscillation etc. [4-16]. Among these, the scheme based on the SBS has attracted particular attention since it can provide a simpler and more flexible way compared to the others by enabling arbitrary control of the gain shape leading to spectral tailoring of the group index variation.

This presentation will provide an overview of the progress in the Brillouin slow light technology since the first demonstration in 2005. The brief history, the basic principle, and current research activities will be introduced with selective and significant experimental results. The fundamental and the practical limitations of the slow light systems will be also discussed that give rise to the needs to search for new application fields other than all-optical buffers in communication systems.

Principle of Brillouin slow and fast light

All the slow and fast light schemes exploit abrupt phase-index variation (Δn) near narrowband spectral resonance of optical media that induces large group index change (Δn_g) based on the Kramers-Kronig relation [1]. The Brillouin slow light in optical fibers applies narrowband Brillouin gain or loss spectra for the control of the group index. As depicted in Fig. 1(a), an optical wave propagating in one direction along an optical fiber provides a narrowband ($\Delta\nu_B = 30 \sim 50$ MHz) Brillouin gain or loss to counter-propagating signals of specific optical frequencies (Stokes or anti-Stokes) by SBS process. The Lorentzian-shaped Brillouin gain (or loss) induces a sudden change of Δn and Δn_g with local maxima (or minima) δn and δn_g which are expressed as following equations [13]:

$$\delta n = \frac{c}{8\pi\nu_c} g_B I_P \quad (1)$$

$$\delta n_g = \frac{4\nu_c \cdot \delta n}{\Delta\nu_B} = \frac{c \cdot g_B I_P}{2\pi \cdot \Delta\nu_B} \quad (2)$$

where c, ν_c, g_B, and I_p are speed of light in vacuum, center frequency of Brillouin gain, Brillouin gain coefficient, and intensity of pump wave, respectively.

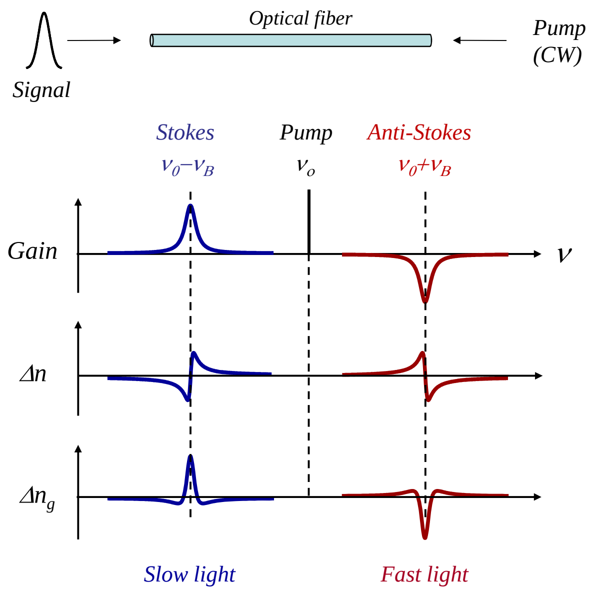

Fig. 1. Configuration of Brillouin slow and fast light with the schematic view (upper), and Δn and Δn_g induced by Brillouin gain and loss spectrum (lower).

The induced time delay is expressed in a simple form as follows:

$$\Delta T = \frac{g_B L}{2\pi} \cdot \frac{I_P}{\Delta\nu_B} = \frac{G}{2\pi \cdot \Delta\nu_B} \quad (3)$$

where L is the length of the fiber and G is the exponent of the Brillouin gain, respectively. Eq. (3) shows that the amount of the time delay linearly depends on the pump power. In conventional single-mode fibers, one can get the time delay of 1 ns per dB gain [4]. Since Δn_g only depends on the pump power according to Eq. (2), one can achieve large variation of the group velocity if a short length of fiber is used and a pulse operation of the pump is applied. When a 2 m fiber was used with a pulse operation of the pump, both a three-fold slowing down and a negative group velocity were observed [6].

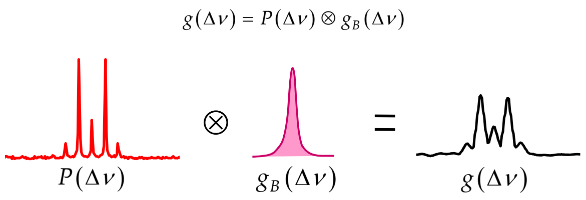

Fig. 2. Schematic of the tailoring of Brillouin gain spectrum.

One of significant improvements of the Brillouin slow light is the use of broadband pump [10]. As depicted in Fig. 2, the gain spectrum (*g*) induced by broadband pump waves is given by the convolution between the intrinsic Brillouin gain spectrum (g_B) with a Lorentzian shape and the pump spectrum (*P*). When the pump spectrum is broad enough (>> 30 MHz), the shape of the Brillouin gain simply follows the shape of the pump spectrum, which opens the way to arbitrarily control the spectral shape of Δn_g. A number of interesting results have been reported based on the tailoring of the pump spectrum such as gain-assisted fast light [7, 13], distortion management [17-19], zero-gain slow light propagation [20-21], broadband slow light [10, 22-24] etc.

The use of broadband pumps raises the problem of the drop of the efficiency as described in Eq. (2), which strongly motivates the use of specialty optical fibers that are featured by much larger Brillouin gain coefficients than that of conventional silica fibers. Specialty fibers made of bismuth-oxide, chalcogenide glass, and tellurite glass have shown much higher Brillouin efficiency than that of ordinary silica fibers by up to ~ 100 time, thanks to their larger gain coefficients originating from larger refractive indexes [11-13]. At the same time, specialty fiber-based slow light systems suffer from large propagation losses of up to 1 dB/m and difficulty of the handling, which deteriorates their practicality. However, some of them like the un-doped tellurite-glass fiber show an advantage of low propagation loss as small as 0.054 dB/m while the Brillouin gain coefficient is ~ 20 times larger than that of ordinary silica fibers [13]. Thus it is expected to be a good candidate for the efficient Brillouin slow light medium.

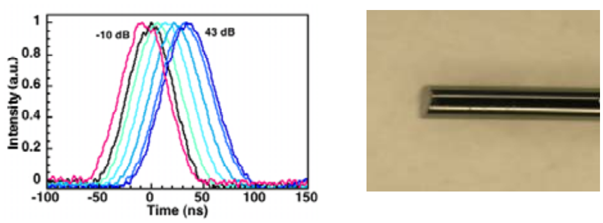

Fig. 3. Experimental result of Brillouin slow light (left) using a 5 m As_2Se_3 chalcogenide fiber (right)

As reported by many valuable studies [25-27], the storage capability of slow and fast light delay lines based on amplifying spectral resonances such as the SBS is still far below the expectations to be used for optical buffers in optical communication systems. Probably, other technologies, such as wavelength conversion associated with a dispersive optical medium can be an efficient solution for the application with much larger storage capacity [28-29]. Coherent optical storage also appears to be a promising approach, and recent results show that the SBS can realize the storage function in optical fibers [30].

Besides the application as an optical buffer in the all-optical communication systems, there are other kinds of possible applications of the Brillouin slow light. For instance, it has been recently reported that the Brillouin slow light-based delay line could be a robust solution in the retiming applications in digital transmissions requiring an error-free one-bit delay [31]. Since one or two bit time delay is sufficient for the applications in analog signal processing such as microwave photonic applications and phased-array antennas, the Brillouin slow light can become a very attractive solution. In addition, the linear response of the time delay to the pump power can provide another advantage, as the linearity is another essential requirement for analog systems [3].

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