# Simple technique to achieve fast light in gain regime using Brillouin scattering

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**Abstract:** We describe a novel technique based on stimulated Brillouin scattering for propagating fast light (signal advancement) with low distortion in optical fibers. The essence of the technique relies on the presence of two separate gain resonances in the Brillouin gain spectrum generated by cascading two different fiber segments showing distinct Brillouin shifts. It can be shown that in between these two gain spectra, a reduced group index can be obtained. To further optimize our results, we broadened the pump spectrum by introducing a modulation of the current driving the pump laser to achieve a delay-bandwidth product close to the optimum conditions. This scheme eliminates the need of an external optical modulator and offers the advantage of a much reduced signal distortion.

**OCIS codes:** (060.4370) Nonlinear optics, fibers; (290.5900) Scattering, stimulated Brillouin; (350.5500) Propagation

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## 1. Introduction

The control of the speed of light in optical media is attracting an increasing interest from the scientific community. The possibility to exert an optical control on the group velocity of an optical signal could have important implications for all-optical signal processing, for example to achieve optically-controlled delay lines and to develop fast-access memories. Fast light experiments are particularly challenging and fascinating for the scientific community, since superluminal signal velocities can be achieved (however preserving Einstein’s causality). These experiments require reaching a very large anomalous dispersion in the medium at the signal frequency. Sharp atomic absorptions and electromagnetically-induced absorption (EIA) have provided efficient means to obtain this large anomalous dispersion. In optical fibers the narrowband absorption of stimulated Brillouin scattering has been successfully used to create these conditions [1-3]. All these methods for obtaining fast light, however, have the common drawback of making the pulse propagate in a spectral region of high absorption. To overcome this impairment, two methods have been devised: one is to propagate the pulse in a region slightly detuned from a gain line, where the group velocity change is negative; the other, more sophisticated approach is to make use of the large anomalous dispersion appearing between two gain peaks. These methods have been previously demonstrated in atomic vapours [4,5].

In a previous paper [6] we reported the first experimental demonstration of pulse advancement with gain in optical fibers using stimulated Brillouin scattering (SBS). We tested the two methods described above to achieve gain-assisted fast light and demonstrated experimentally that the method based on the double Brillouin gain peak produces pulse advancement with lower distortion. The experiment was done by externally modulating the pump to create two spectral lines whose separation is controlled by the modulation frequency. The group index change is directly proportional to the pump intensity, enabling a simple control of the signal advancement. However, the distortion achieved in these experiments was still far from ideal. A similar technique using the anti-Stokes bands was used in [7] to achieve nearly-transparent slow-light, that is, slow light with only minor amplitude changes. Fully transparent slow & fast light was nevertheless achieved recently using a two pump scheme, by spectrally superposing gain and loss spectra with different spectral width [8]. In [7] it was shown that an optimized delay-bandwidth product can be obtained by a suitable relationship between the separation of the resonances and their width.

The system described in the present paper is conceptually similar to those developed previously in [6,7], but it has two crucial advantages: first, it eliminates the need of an external electro-optic modulator, drastically simplifying and optimizing the operation; second, it makes the operation in the optimum delay-bandwidth product conditions easily possible. The setup proposed here simply consists of two appended fiber segments with different Brillouin shifts. This causes naturally and passively the generation of two spectrally close Brillouin gain resonances using a single pump and with no need to insert any kind of modulator, as far as the total gain after propagation through the 2 segments is considered. To optimize the delay-bandwidth product, a definite pump broadening is introduced by direct current modulation of the pump laser. The width of the gain resonances can be adjusted this way to closely match the optimum value relating the separation of the resonances and their width [7].

## 2. Principle

Stimulated Brillouin scattering (SBS) in optical fibers is a nonlinear interaction between two counter-propagating waves, a strong pump wave at $\nu_{pump}$ and a weak probe wave at $\nu_{probe}$. Under certain phase matching conditions, ($\nu_{pump}=\nu_{probe}+\nu_B$, $\nu_B$ being the Brillouin shift), an acoustic wave is generated by interference and electrostriction. When this acoustic wave is present, photons from the pump are scattered to the probe, leading to a stronger interference

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and a larger acoustic wave, therefore stimulating the process. From a system point of view, SBS can be viewed as narrowband amplification (30-50 MHz) created by the pump around the frequency $\nu_{pump}$-$\nu_B$. The Brillouin shift is given by $\nu_B=2nV_a/\lambda$ where $n$ is the refractive index, $\lambda$ is the wavelength of the pump in vacuum and $V_a$ is the acoustic velocity within the fiber. Since the Brillouin shift $\nu_B$ is determined by the velocity of the acoustic grating along the fiber, it can be readily influenced by changing the mechanical properties of the fiber such as the applied strain or the ambient temperature [9,10]. In addition, the frequency shift is also affected by the doping concentrations in the core and cladding of the fiber [10].

Let us now consider two spliced segments of optical fibers with similar length but different core doping concentrations (and hence different Brillouin shifts) as shown in Fig. 1 From a qualitative point of view, it can be seen that each fiber segment will have the Brillouin gain curve tuned at a different position, and hence two gain resonances will appear in the spectrum of the full system. In these conditions, anomalous dispersion appears in the middle of the gain doublet and therefore, pulse advancement or fast light can be realized when the signal pulse is spectrally positioned in the valley between the two peaks.

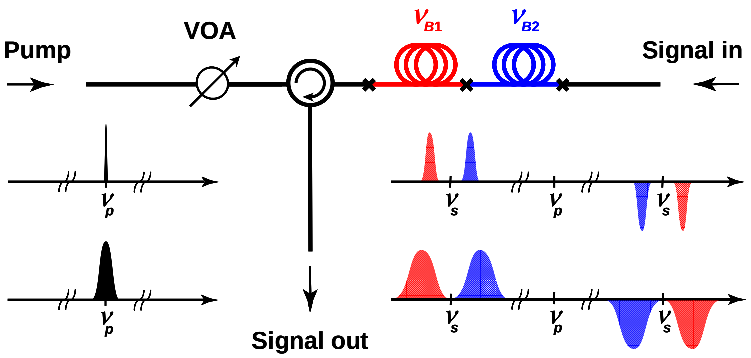

Fig. 1. Principle of the single-pumped passive configuration to generate a SBS gain or loss doublet. A partial overlap of the gain spectra can be created by using a spectrally broadened pump, as shown on the bottom situation.

The evolution of the probe wave intensity along the fibers will be given by the following equation:

$$\frac{dI_S}{dz} = g_B(z,\nu) I_P I_S - \alpha I_S \tag{1}$$

where $I_P$ and $I_S$ are, respectively, the pump and probe intensities, $\alpha$ is the attenuation coefficient of the fiber and $g_B(z,\nu)$ is the natural Brillouin gain curve at each position, given by the usual Lorentzian shape:

$$g_B(z,\nu) = g_B \frac{1}{1-2j\left[\left(\nu - \nu_B(z)\right)/\Delta\nu_B(z)\right]} \tag{2}$$

where $\nu$ is the pump-probe frequency difference and $\Delta\nu_B$ is the FWHM width of the Brillouin gain spectrum. Assuming negligible pump depletion, the evolution of the counter-propagating pump intensity can be written as:

$$I_P(z) = I_0 \exp\left(-(L-\alpha)z\right) \tag{3}$$

where $I_O$ is the pump intensity launched into the far end of the fiber and $L$ the fiber length. Inserting (3) into equation (1) the following explicit expression is obtained for $I_S$ at the output:

$$I_S(L) = I_S(0)\exp\left(I_0\int_0^L \left[g_B(z,\nu)\exp(-\alpha z) - \alpha\right]dz\right) \tag{4}$$

In the case depicted in Fig. 1 and assuming that the Brillouin linear gain $g_B$ is position-independent in each fiber segment, the signal intensity reads:

$$I_S(L) = I_S(0)\exp\left(-\alpha(L_1 + L_2)\right)\exp\left(I_0\left[g_{B2}(\nu_2)L_{2eff} + g_{B1}(\nu_1)L_{1eff}\exp(-\alpha L_2)\right]\right) \tag{5}$$

where $g_{B1}$ and $g_{B2}$ are the Brillouin linear gains of each fiber segment respectively, $L_1$ and $L_2$ are the lengths of the fiber segments, and $L_{1eff}$ and $L_{2eff}$ are their corresponding usual nonlinear effective lengths [11]. Hence the total gain spectrum observed at the output of fiber 2 is the superposition of the gain spectra accumulated along the two fibers, with different weights depending on the relative ordering of the fiber segments, their length and a possible different Brillouin linear gain. Assuming a small loss, the two resonances will show nearly identical strength for equally long fiber segments.

In the case of a spectrally-broadened pump, the same superposition rule holds, provided that $g_B$ in all the expressions is replaced by the effective gain curve $g$ [12]:

$$g(\Delta\nu) = P(\Delta\nu) \otimes g_B(\Delta\nu) \tag{6}$$

where ⊗ denotes convolution and $P(\Delta\nu)$ is the normalized pump power spectral density (integral over spectrum is unity). For a Lorentzian shape of the pump spectrum, the effective gain curve remains Lorentzian, and its width is given by $\Delta\nu_B+\Delta\nu_P$, $\Delta\nu_P$ being the width of the pump spectrum.

This way, two separate gain or loss windows with arbitrary bandwidth may be naturally opened in the Stokes and the anti-Stokes regime. These, in turn, can induce anomalous dispersion or normal dispersion in the middle of the gain or loss doublets, respectively. Hence, pulse advancement or fast light can be observed when the signal is spectrally placed at the center of the gain doublet. On the contrary, an equivalent temporal delay or slow light can be produced as well by simply tuning the signal frequency in between the absorption doublet.

In [7] it was shown that the optimum delay-bandwidth product for the two-resonance scheme is achieved for a particular ratio between the separation of the resonances and their width. Applied to our scheme, this relationship should be approximately $(\nu_{B1}-\nu_{B2})/\Delta\nu_B\approx 3$. In the experimental scheme used in this paper, $\nu_{B1}-\nu_{B2}$ is approximately 120 MHz, so we broaden the spectrum of the Brillouin interaction from its characteristic value of 25 MHz to approximately 40 MHz, to be in the optimum delay-bandwidth product conditions. This is done simply by introducing a noise modulation of the current passing through the pump laser, in a similar way to the one developed in [12] and later extended to extreme bandwidths in [13,14].

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## 3. Experiments and Results

Figure 2 depicts the schematic diagram of the experimental set-up. We appended two segments of different single mode optical fibers with similar length (approximately 2km) as the SBS gain medium. These two fibers are both step index single mode fibers, showing a 20% difference in core doping concentration and in the core radius, resulting in a Brillouin shift difference of 120 MHz [10]. Two conventional temperature and current-controlled distributed-feedback (DFB) lasers operating at a wavelength of 1532 nm are used to generate the pump beam and the probe beam, respectively. The pump laser is directly modulated using a noise generator in order to broaden its spectral linewidth through the current-frequency dithering effect. Then the pump power is amplified using an erbium doped fiber amplifier (EDFA) and is adjusted by a variable optical attenuator before routing via a circulator to pump the cascaded optical fibers. The spectral width of the pump is simply controlled by varying the amplitude of the noise signal. When the pump modulation is turned off, two well separated natural SBS gain/loss resonances are observed with a central frequency spacing of about 120 MHz ($\nu_{B1} - \nu_{B2}$). The frequency separation remains perfectly stable in this experiment since there is no applied strain and/or temperature variations around the fibers. It must be pointed out that a temperature variation would only cause a global spectral shift of the 2 resonances, but their frequency difference would remain constant [9]. The two Brillouin resonances show basically identical Brillouin bandwidth of approximately 25 MHz.

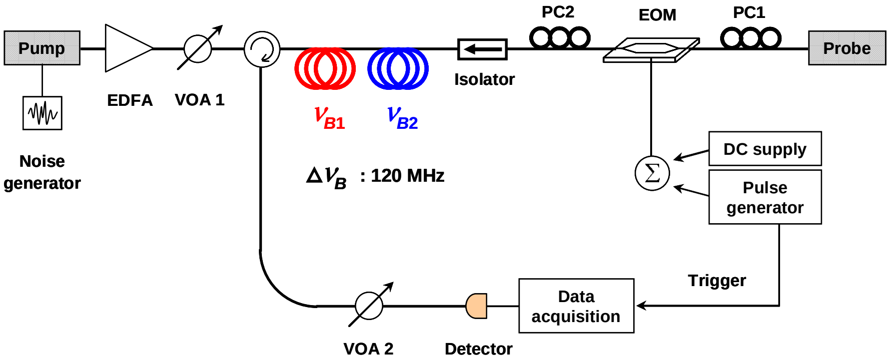

Fig. 2. Experimental setup to realize a fast light propagation with low distortion, by appending two optical fibers showing different Brillouin shift and by using a spectrally broadened pump laser. EDFA: erbium doped fiber amplifier, VOA: variable attenuator; EOM: electro-optic modulator, PC: polarization controller

To observe the shape of the gain doublet, we used a frequency-sweeping laser and measure the signal amplitude at the end of the fiber. Figure 3 shows the gain doublet generated by the proposed method for different values of the pump spectral width while the pump power is kept constant. It is seen that the two gain peaks of Brillouin amplification are slightly mismatched mainly as a result of the pump attenuation after propagation in the first fiber segment, but the measurement experimentally confirms the adequacy of the expression in Eq. 5. It turns out that the total gain is given by the superposition of the individual gains in each fiber.

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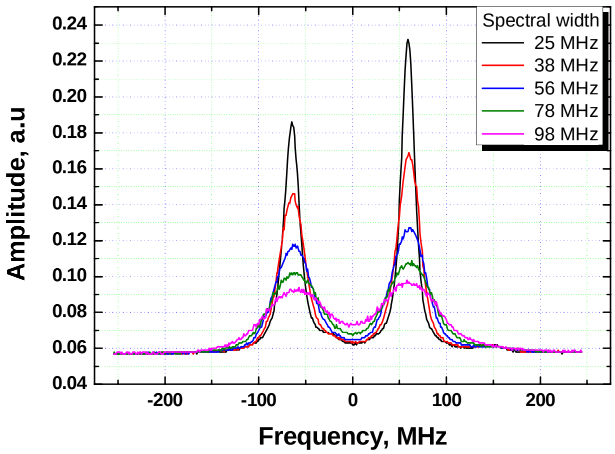

Fig. 3. The spectral profiles of gain-doublets as a function of frequency for different spectral widths of the pump. Pump power is kept constant.

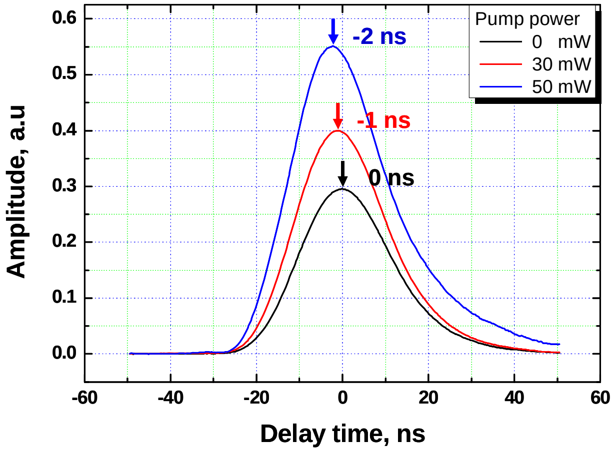

Fig. 4. The non-normalized traces of the pulsed probe signal with different pump powers, showing clear advancements and the absence of visible distortion.

The probe signal pulse is generated from a distinct DFB laser. The laser passes through an optical isolator, a fiber polarization controller and is optically gated using a fast external electro-optic modulator (EOM) to produce a pulse train. The probe pulse then enters the compound fiber in opposite direction to the pump beam. The frequency of the probe is precisely tuned by adjusting the temperature and current settings applied to the laser, so that the center frequency of the pulse is accurately placed in the middle of the two Brillouin gain resonances. The PC1 is used to maximize the transmission through the Mach-Zehnder EOM and the PC2 is used to make the polarization of the probe best match that of the pump in order to maximize the pulse advancement.

The temporal advancements and amplitudes of the probe pulses after propagating through the fiber cascade are measured and displayed on a digital oscilloscope for different values of pump power and pump linewidth. Optimized results are found when the width of the effective gain curves of the fiber segments reaches approximately 40 MHz. The FWHM pulse width used in this experiment is about 25 ns and the pulses have a Gaussian-like intensity profile with smooth edges, though showing a somehow longer trailing edge. Fig.4 shows the non-normalized time waveforms of the pulses after experiencing the fast light propagation through the fibers for values of pump power of 0 mW, 30 mW and 50 mW, respectively. It is clearly observed that signal advancement is achieved with minor signal distortion and reduced signal amplification. The pulse broadening is only apparent, since we do not present normalized time traces to demonstrate the moderate amplitude change. Normalized traces would show a very minor distortion that results from the spectral filtering (high-pass filtering) in a fast light process. This mostly results in modified leading and trailing edges, but does not really impact on the broadening. The largest signal advancement achieved is about 2 ns with 2.7 dB signal amplification at the pump power of 50 mW. Evaluating the FWHM spectral width of the valley through simple arithmetics to be approximately 80 MHz, an equivalent delay would be associated with a 6.4 dB gain or loss using a standard single resonance configuration, showing clearly that the output power variation is substantially reduced.

To accurately determine the amount of signal advancement induced by the proposed scheme we used a sinusoidally modulated light to avoid any biasing due to a possible distortion. This way we unambiguously measure the real time advancement without any arbitrary criterion, by measuring the phase shifts of the sine wave. Figure 5 shows the achieved time advancement as a function of the pump power, showing that the signal advancement has a linear dependence along the pump power with a slope efficiency of approximately 0.04 ns/mW.

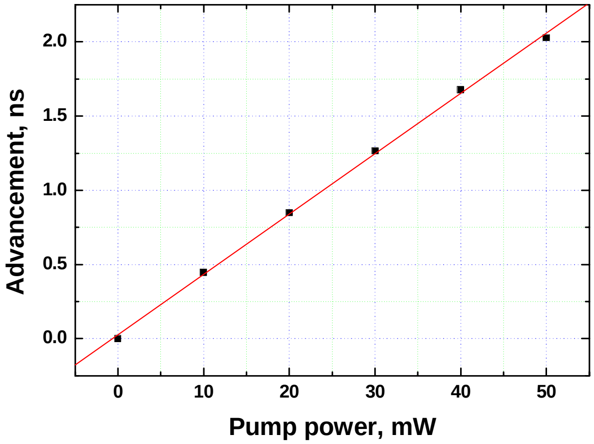

Fig. 5. Time advancements for a 1 MHz sine modulated signal as a function of the pump power in the optimum delay-bandwidth conditions (resonance separation: 120 MHz, effective resonance width 40 MHz).

This technique cascading fibers can also be applied to produce slow light, by simply placing a pulse spectrally in the center of a loss doublet, occurring in the Anti-Stokes regime. In this condition a large normal dispersion is observed in the valley of the two peaks and the refractive group index is increased with pump power. In this case, the pump source was also spectrally broadened by means of direct modulation in order to optimize the characteristics of the slow light medium. This configuration was also experimentally tested and Fig. 6 shows the obtained delays. The insert presents the measured Brillouin loss doublet created in the Anti-Stokes regime while the pump propagates through the cascaded fiber segments. As anticipated, we observed a linear dependence of the time delay on the pump power, showing a slope efficiency of approximately 0.03 ns/mW.

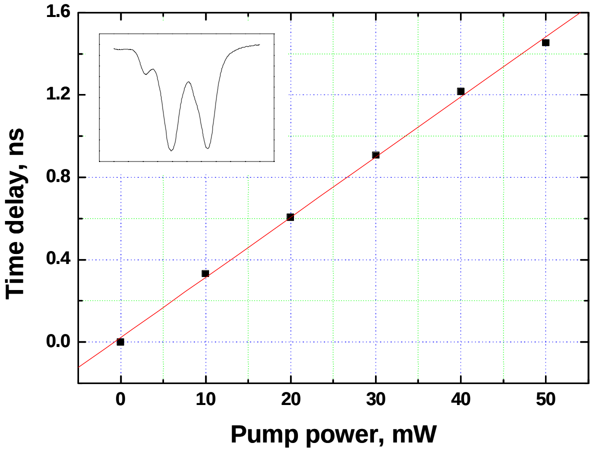

Fig. 6. Temporal delays for 1 MHz sine modulated signal with respect to the pump power after propagating through two different optical fibers. Insert shows the Brillouin loss doublet created in the Anti-Stokes regime.

## 4. Conclusions

We have described a new method for achieving fast light (signal advancement) with low distortion in optical fibers based on cascading two fiber segments with different Brillouin shifts. This causes the generation of two separate gain resonances in the Brillouin gain spectrum. It must be pointed out that the gain resonance separation can be much larger than 1 GHz by properly selecting the optical fibers [10]. In the median part of these two gain spectra, a reduced group index can be obtained. To work in the optimum delay-bandwidth conditions, we broaden the pump spectrum by introducing a modulation of the current going through the pump laser. Additionally, compared to previous setups, this scheme eliminates the need of any external optical modulator. We have shown the capabilities of the technique by working close to the optimum conditions. In particular, fractional advancements of roughly 10% can be obtained with negligible distortion. Using this concept, the bandwidth limitation is determined by the difference of Brillouin shifts. It is not difficult to find two fibers whose Brillouin shift is separated by at least 1 GHz, such as standard and dispersion compensating fibers, extending the data rate to at least 1Gbit/s. In order to separate them further, we can elongate one of these two fibers. This way we can shift the Brillouin frequency by 500 MHz/% [10], resulting in a further extended bandwidth. Higher resonance separation would require fibers manufactured in different materials, such as fluoride and chalcogenide glasses showing Brillouin shifts several GHz lower than silica [15,16]. This demonstrates the unmatched flexibility offered by stimulated Brillouin scattering to produce slow and fast light, here illustrated by combining the fiber-dependent natural properties of the interaction with a fine engineering of the pump spectrum.

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