Low distortion Brillouin slow light in optical fibers using AM modulation

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Abstract: Stimulated Brillouin scattering (SBS) has been recently shown to offer a mechanism for generating tunable all-optical delays in room-temperature single-mode optical fibers at telecommunication wavelengths. This technique makes use of the rapid variation of the refractive index that occurs in the vicinity of the Brillouin gain resonance. When the slow light pulse delay is subject to a constraint on the allowable pulse distortion, it has been shown that the use of a pair of closely-spaced Brillouin gain lines can increase the distortion-constrained delay, with respect to the single-line configuration. In this paper, we numerically and experimentally demonstrate that the same experimental apparatus usually employed for generating a Brillouin gain doublet, can also be used for achieving three equally-spaced Brillouin gain resonances, further increasing the distortion-constrained pulse delay.

OCIS codes: (060.5530) Pulse propagation and solitons; (290.5900) Scattering, stimulated Brillouin

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References and Links

1. L. V. Hau, S. E. Harris, Z. Dutton, and C. H. Behroozi, "Light speed reduction to 17 metres per second in an ultracold atomic gas," Nature (London) **397**, 594 (1999).
2. M. S. Bigelow, N. N. Lepeshkin, and R. W. Boyd, "Observation of Ultraslow Light Propagation in a Ruby Crystal at Room Temperature," Phys. Rev. Lett. **90**, 113903 (2003).
3. 3. J. Sharping, Y. Okawachi, and A. Gaeta, "Wide bandwidth slow light using a Raman fiber amplifier," Opt. Express **13**, 6092-6098 (2005).
4. K. Y. Song, M. G. Herráez, and L. Thévenaz, "Observation of pulse delaying and advancement in optical fibers using stimulated Brillouin scattering," Opt. Express **13**, 82-88 (2005).
5. Y. Okawachi, M. S. Bigelow, J. E. Sharping, Z. M. Zhu, A. Schweinsberg, D. J. Gauthier, R. W. Boyd, and A. L. Gaeta, "Tunable all-optical delays via Brillouin slow light in an optical fiber," Phys. Rev. Lett. **94**, 153902 (2005).
6. K. Song, M. Herráez, and L. Thévenaz, "Long optically controlled delays in optical fibers," Opt. Lett. **30**, 1782-1784 (2005).
7. R. W. Boyd, D. J. Gauthier, A. L. Gaeta, and A. E. Willner, "Maximum time delay achievable on propagation through a slow-light medium," Phys. Rev. A **71**, 023801 (2005).
8. H. Cao, A. Dogariu, and L. J. Wang, "Negative group delay and pulse compression in superluminal pulse propagation," IEEE J. Sel. Top. Quantum Electron. **9**, 52-58 (2003).
9. B. Macke and B. Ségard, "Propagation of light-pulses at a negative group-velocity," European Phys. J. D **23**, 125-141 (2003).
10. M. Bashkansky, G. Beadie, Z. Dutton, F. K. Fatemi, J. Reintjes, and M. Steiner, "Slow-light dynamics of large bandwidth pulses in warm rubidium vapor," Phys. Rev. A **72**, 033819 (2005).
11. Z. Dutton, M. Bashkansky, M. Steiner, and J. Reintjes, "Channelization architecture for wide-band slow light in atomic vapors," SPIE 5735, 115-129 (2005).
12. Q. Sun, Y. V. Rostovtsev, J. P. Dowling, M. O. Scully, and M. S. Zhubairy, "Optically controlled delays for broadband pulses," Phys. Rev. A **72** 031802(R) (2005).
13. M. Stenner, M. Neifeld, Z. Zhu, A. Dawes, and D. Gauthier, "Distortion management in slow-light pulse delay," Opt. Express **13**, 9995-10002 (2005).

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14. K. Song, M. González Herráez, and L. Thévenaz, "Gain-assisted pulse advancement using single and double Brillouin gain peaks in optical fibers," Opt. Express 13, 9758-9765 (2005).
15. M. González Herráez, K. Song, and L. Thévenaz, "Arbitrary-bandwidth Brillouin slow light in optical fibers," Opt. Express 14, 1395-1400 (2006).
16. Z. Zhu, A.M.C. Dawes, D.J. Gauthier, L. Zhang, and A.E. Willner, "12-GHz-Bandwidth SBS Slow Light in Optical Fibers," postdeadline paper PDP1, OFC 2006, Anaheim, CA, Mar. 5-10, 2006.
17. D. Dahan and G. Eisenstein, "Tunable all optical delay via slow and fast light propagation in a Raman assisted fiber optical parametric amplifier: a route to all optical buffering," Opt. Express 13, 6234-6249 (2005).
18. A. V. Oppenheim and A. S. Willsky, Signals and Systems, 2nd Ed. (Prentice Hall, Upper Saddle River, 1997).
19. G. P. Agrawal, Nonlinear fiber optics, 3th Ed. (Academic Press, Boston, 2001).
20. M. Nikles, L. Thévenaz, and P. A. Robert, "Brillouin gain spectrum characterization in single-mode optical fibers," J. Lightwave Technol. **15**, 1842-1851 (1997).

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1. Introduction

The possibility to optically control pulse delays is of great importance in applications such as optical buffers, data synchronization, optical memories, and signal processing. Slow light can be achieved, for example, using the large normal dispersion associated with a resonance of a material system. Early slow light research usually has used electromagnetically induced transparency (EIT) [1] or coherent population oscillations [2], in which a narrow transparent window is created within an absorbing resonance by an intense coupling laser field.

Slow light is also possible using the dispersion associated with a laser-induced amplifying resonance such as that arising from stimulated Raman scattering (SRS) [3] and stimulated Brillouin scattering (SBS) [4-6]. In particular, the demonstration of optically controllable slow light delays at telecommunication wavelengths via SBS in a conventional single-mode optical fiber has attracted a great interest, because of the different advantages that the SBS process offers with respect to other techniques, such as the possibility to create the resonance at any wavelength through a simple change of the pump wavelength, the low-power requirement owing to long interaction lengths and small mode areas, and room-temperature operation.

In applications making use of slow light, real interest lies in demonstrating delays approaching and exceeding the pulse width. Hence, the efficiency of the slow light medium is measured in terms of maximum relative pulse delay, the latter being defined as the pulse delay normalized to the pulse width. An additional requirement is that the pulse not be substantially distorted. Unfortunately, these two requirements largely oppose each other, with large delay coming at the cost of greater distortion. While these trade-offs have been studied in simple systems [7-10], there is a strong interest in designing slow light media which permit to achieve a large relative delay without incurring in too much distortion.

The capability of a slow light medium to delay shorter pulses is essential for enabling the processing of digital data streams at increasing data rates. To reduce the minimum pulsewidth that can be used effectively in a slow light element, the resonance bandwidth has to be increased. For slow light media based on EIT in atomic vapors, a technique involving the application of a magnetic field with a linear gradient has been recently proposed in order to increase the bandwidth of the pulses to be delayed [11,12]. For SBS-based slow light in an optical fiber, the use of a double Brillouin gain peak configuration has been demonstrated to increase the maximum relative pulse delay [13,14] with respect to the SBS single resonance configuration. Pump spectrum broadening by direct current modulation of a distributed feedback (DFB) semiconductor laser has been also proposed for SBS-based slow light [15,16]. An operation bandwidth up to 12.6 GHz has been demonstrated by using the latter approach. Such a bandwidth approaches the ultimate bandwidth achievable by using slow light SBS-based systems, which is in the order of twice the Brillouin frequency shift, the limitation being due to the overlap between the gain feature at the Stokes frequency and the absorption feature at the anti-Stokes frequency [16]. Even wider bandwidths have been demonstrated by employing other nonlinear effects occurring in optical fibers. For example, an operation bandwidth of 150 GHz was demonstrated in Ref. [17] by using optical

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parametric amplification coupled with Raman process. Such a bandwidth is sufficiently wide to process digital data streams at tens of Gbit/s rates as well as picoseconds pulses.

As the effectiveness of a slow light medium consists in delaying a pulse without introducing too much distortion, it is useful to introduce a method aimed to determine the optimal parameters of the resonance medium, such that the relative pulse delay is maximized while subjecting the pulse to a constraint on the allowable pulse distortion. Stenner *et al* [13] recently proposed a technique of distortion management which can be applied to any dispersive medium, as it defines a distortion metric which is applied directly on the transfer function relating the output pulse spectrum to the input pulse spectrum. In this way, it is possible to determine the optimal slow light medium physical parameters which maximize the relative pulse delay, under the constraint that the distortion and the gain do not exceed a particular limit. In this paper we apply the above mentioned distortion management technique, to the case of a dispersive medium constituted by three equally-spaced Lorentzian gain lines. Single-line and double-line configurations are also considered for comparison purposes. Numerical results indicate that the gain triplet outperforms both single-line and double-line configurations under conditions of constant distortion. In particular, a longer distortion-constrained delay is possible for short pulses ($\tau < 20$ ns in our experimental conditions) by optimizing the physical parameters which define the gain triplet. Experimental results confirm the numerical predictions, where the slow light effect arising from stimulated Brillouin scattering in a pumped optical fiber is exploited, and the multiple-resonance structure is achieved by intensity-modulating the optical wave used as the pump. It is important to underline that an experimental apparatus similar to the one used in Ref. [13] and Ref. [14] for Brillouin gain doublet configuration has been used for our experiments, while we show that the selection between the double-gain and the triple-gain configuration can be simply performed by adjusting the bias voltage of the Mach-Zehnder modulator employed for pump wave modulation.

The paper is organized as follows: In the next section we will briefly recall the distortion management technique proposed in [13]. The single-line, double-line and triple-line cases are then numerically analyzed. A number of experimental results is finally presented, carried out in both double-line and triple-line configuration.

2. Theory

When an optical pulse propagates through a linear optical system, the output pulse amplitude $A(\omega,z)$ in the frequency domain can be related to the input pulse amplitude $A(\omega,0)$ by

$$A(\omega, z) = A(\omega,0)\exp(jk(\omega)z), \tag{1}$$

where z is the length of the medium and $k(\omega)$ is the complex wavenumber as a function of frequency ω. A pulse propagates undistorted through a dispersive material when $k(\omega)$ takes the form

$$k(\omega) = k_0 + k_1(\omega - \omega_c), \tag{2}$$

where ω_c is the carrier frequency of the pulse and k_1 is real. That is, the pulse shape remains unchanged and the only effects of propagation are delay, an overall phase shift, and gain or attenuation. In this ideal case, the pulse delay t_d is equal to the group delay $t_g = z(k_1 - 1/c)$, where c is the speed of light in vacuum. When the dispersive medium has higher-order terms in the Taylor expansion $k(\omega) = \sum_{j=0}^{\infty} k_j (\omega - \omega_c)^j / j!$, with $k_j \equiv d^j k(\omega)/d\omega^j$, pulse

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distortion can occur. When longer pulses are considered, the linearity of k(ω) over the pulse bandwidth improves, but this results in a reduced relative pulse delay. One method for creating delayed pulses with minimal distortion is to reduce the effects of the higher-order terms in the Taylor series expansion of $k(\omega)$ by using custom slow light media designed to minimize the effects of distortion. While creating a custom dispersion profile $k(\omega)$ is in general quite difficult, an opportune slow light system can be created by combining simple systems. For example, the case of a dispersion law given by the superposition of a number of gain or absorption doublets has been theoretically analyzed in [9]. For this system, each additional doublet provides two new degrees of freedom, given by their gain g_{0r} and their line-splitting parameter δ_k, and the use of r doublets allows us in principle to cancel the higher-order terms in the Taylor series expansion of $k(\omega)$ up to the order $2r$. More generally, it can be expected that a higher number of free parameters in the design of $k(\omega)$ permits to increase the maximum relative pulse delay, while keeping a constraint on the allowable pulse distortion. As pulse distortion occurs whenever the dispersion law deviates from the ideal law described in Eq. (2) [18], a practical approach to distortion management is to measure distortion as the deviation of the medium from the ideal case. Describing the medium in terms of its transfer function $H(\omega)=\exp(jk(w)z)$, a criterion to quantify such a deviation is to calculate the infinity-norm – the maximum magnitude – of the amplitude and phase deviation of the medium transfer function from the ideal transfer function given by $H_0=\exp[i(k_0-k_1\omega_0)z]$ [13]. This approach leads to two distortion metrics, one for the amplitude variation (D_a) and one for the phase variation (D_p). The amplitude distortion is given by

$$D_a=\frac{H_{\max}-H_{\min}}{H_{\max}+H_{\min}}, \tag{4}$$

where $H_{\min}$ and $H_{\max}$ are the minimum and maximum values of $|H(\omega)|$ over the frequency range ($\omega_0-\Delta_b, \omega_0+\Delta_b$). Similarly, the phase distortion is defined as

$$D_p=\frac{1}{2\pi}\max\left[\left|\angle H(\omega)-(t_p\omega+\phi_0)\right|\right]_{\omega_0-\Delta_b}^{\omega_0+\Delta_b}. \tag{5}$$

where t_p and ϕ_0 are chosen to minimize D_p. This provides a distortion measure which is reasonable for pulses whose power is mostly concentrated within the frequency range ($\omega_0-\Delta_b$, $\omega_0+\Delta_b$). The calculation of D_p also serves to define an effective propagation time t_p as the propagation time of a pulse through the ideal medium which most closely approximates the real medium. As discussed in [13], a delay defined in terms of this propagation time $t_d=t_p-n_0\,z/c$ is similar in concept to the group delay, except that it is based on the material dispersion over the entire bandwidth of interest rather than just at the carrier frequency.

3. Results and discussion

The distortion management discussed in the previous section will be now applied to the cases of a single Lorentzian gain line, a double Lorentzian gain line, and a triple Lorentzian gain line. The first two cases have been already discussed in [13], and will be here recalled for comparison purposes. The transfer function of a single Lorentzian gain line can be written as

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$$H_1(\omega) = \exp\left(izn_0 \frac{\omega}{c}\right) \times \exp(g_1(\omega))$$
$$= \exp\left(zn_0 \frac{\omega}{c} + g_{01} \frac{i\gamma}{(\omega - \omega_0) + i\gamma}\right), \tag{6}$$

where n_0 is the background refractive index, g_{01} is the line-center amplitude gain, and γ is the linewidth. In this case, the system can be optimized by determining the value of g_{01} that provides maximum pulse delay t_d subject to gain and distortion constraints. In [13], an amplitude gain constraint of $g_{01} \leq 2.5$ was considered. In this paper, we consider $g_{01} \leq 1.5$ because of the limited pump power available for experimental validation. As regards distortion constraint, we will consider the same limits $D_a < 0.05$ and $D_p < 0.05$ as used in [13]. In Fig. 1(a) we report the maximum relative delay $t_d \Delta_b$ as a function of the relative bandwidth Δ_b/γ. The corresponding Lorentzian gain exponent g_{01} is shown in Fig. 1(b). As apparent from Fig. 1(b), two bandwidths regions can be distinguished: For small bandwidths - $\Delta_b/\gamma < 0.26$ – the delay is limited by the gain constraint, whereas for large relative bandwidths - $\Delta_b/\gamma > 0.26$ – the delay is limited by the distortion constraint.

The distortion-managed system constituted by two Lorentzian gain lines is considered next. The transfer function of this system is

$$H_2(\omega) = \exp\left(izn_0 \frac{\omega}{c}\right) \times \exp(g_2(\omega))$$
$$= \exp\left(zn_0 \frac{\omega}{c} + g_{02} \frac{i\gamma}{(\omega - \omega_0 - \delta_2) + i\gamma} + g_{02} \frac{i\gamma}{(\omega - \omega_0 + \delta_2) + i\gamma}\right), \tag{7}$$

where g_{02} is the line-center gain coefficient for the two lines and $2\delta_2$ is the separation between the lines. In this case, optimization can be performed over the two free parameters – g_{02} and δ_2 - to maximize the delay at each Δ_b subject to the same constraints, $D_a < 0.05$, $D_p < 0.05$, and $\max|g_2(\omega)| \leq 1.5$. The distortion- and gain-limited relative delay for the doublet system, as a function of bandwidth, is shown in Fig. 1(a). We also report in Fig. 1(b) the corresponding gain coefficient g_{02} and in Fig. 1(c) the optimal normalized half-line separation, δ_2/γ. Three bandwidths regions can be distinguished in this doublet case: For smaller bandwidths ($\Delta_b/\gamma < 0.26$) the delay is gain-limited. As in this case the distortion limit is not reached, the second line provides no additional benefit (i.e. $\delta_2 = 0$). For bandwidths $\Delta_b/\gamma > 1$, the delay is distortion-limited, so that the maximum gain cannot be reached. For intermediate values of the pulse bandwidth, both distortion and gain constraints are hit simultaneously. Fig. 1(a) shows that a net improvement on the maximum relative delay is possible by using the doublet configuration, with respect to the single-line case.

Let us now consider the case of three equally-spaced Lorentzian gain lines, where the two lateral lines have equal line-center gain coefficients. The transfer function of such a system can be written as

$$H_3(\omega) = \exp\left(izn_0 \frac{\omega}{c}\right) \times \exp(g_3(\omega))$$
$$= \exp\left(zn_0 \frac{\omega}{c} + g_{t01} \frac{i\gamma}{(\omega - \omega_0) + i\gamma} + g_{t02} \frac{i\gamma}{(\omega - \omega_0 - \delta_3) + i\gamma} + g_{t02} \frac{i\gamma}{(\omega - \omega_0 + \delta_3) + i\gamma}\right). \tag{8}$$

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where g_{t01} represents the gain coefficient of the central gain line, g_{t02} represents the gain coefficient of the lateral lines, and δ_3 is line separation. As it will be clear below, a transfer function as described by Eq. (8) can be easily implemented with SBS-based slow light systems, using the same experimental apparatus as the one utilized in [13] for the doublet configuration

In this triplet case, we have three free parameters, constituted by g_{t01}, g_{t02}, and δ_3. Hence, we can optimize over these three parameters to maximize the delay at each Δ_b subject to the same constraints, $D_a < 0.05$, $D_p < 0.05$, and $\max|g_3(\omega)| \le 1.5$. It is important to underline that the limit imposed on the maximum Brillouin gain coefficient guarantees the absence of nonlinear optical effects other than SBS. In particular, it is well known that Four-Wave Mixing (FWM) effect may lead to a coupling between the three participating pump signals [19]. Such a coupling would result in a power transfer from the central gain line to the lateral gain lines, eventually leading to a modified gain spectrum. However, as the parametric gain governing the amplification of the two lateral gain lines is much smaller (about two orders of magnitude) of the Brillouin gain [19] in silica single-mode optical fibers, the parametric interaction between the three gain lines is negligible in our experimental conditions.

The maximum relative delay resulting from the optimization procedure is plotted in Fig. 1(a) as a function of bandwidth. It is seen that the gain triplet permits to increase the maximum relative pulse delay, with respect to both the single-line and the double-line cases. In particular, a maximum relative delay of 0.694 is observed at a bandwidth of $\Delta_b/\gamma = 1.78$ for the triplet case, corresponding to a nearly 20% improvement in comparison to the best two-gain-line case and for the same distortion constraint. We also report in Fig. 1(b) the optimal gain coefficients, and in Fig. 1(c) the normalized line separation, δ_3/γ. Note that the line separation between the three lines is always equal or greater than the optimal half-line separation in the case of the gain doublet. By simultaneously analyzing Figs 1(a-c), it is possible to identify three distinct regions for the triplet gain configuration.

When the bandwidth is small, ($\Delta_b/\gamma < 0.26$) the delay is gain-limited, so that a single line is sufficient to achieve maximum delay. Note that in this region, $\delta_3 = 0$ and $g_{t01} = 0$, so as to result in a single-line configuration. For bandwidths $\Delta_b/\gamma > 1.8$, the delay is distortion-limited, in other words the optimal gain coefficients and line separation imply a maximum gain magnitude less than the imposed limit of 1.5. In the intermediate region, both gain and distortion limit the maximum achievable delay. Note that this intermediate bandwidth region can be further subdivided in two distinct regions: For $\Delta_b/\gamma < 1$, a line separation $\delta_3 > 0$ results from the optimization procedure, while g_{t01} is equal to zero. Hence, in this region the best configuration is constructed by using two nearby Lorentzian gain lines (gain doublet). When $\Delta_b/\gamma > 1$, the gain coefficient of the central gain line g_{t01} is always greater than zero, though it keeps lower than the gain coefficient of the lateral lines, g_{t02}. In this bandwidth region, the best slow light medium is composed of three equally-spaced resonances, allowing for a maximum relative delay outperforming the maximum delay provided by the doublet configuration (see Fig. 1(a)).

To demonstrate the improvement resulting from the use of a gain triplet, a number of experimental tests was performed by exploiting SBS in a single-mode optical fiber. The set-up used for the experiments is shown in Fig. 2. The output light from a DFB diode laser, emitting at 1550 nm wavelength, is split in two by using a 50/50 fiber-fused coupler.

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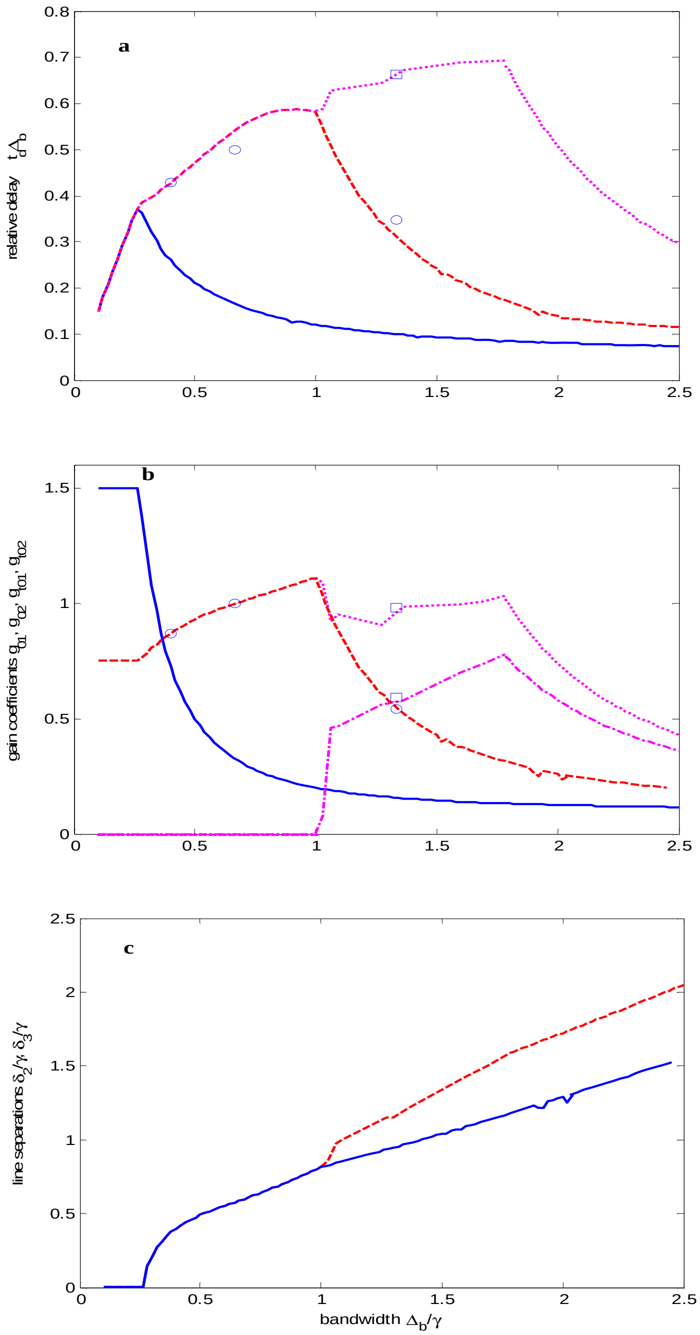

Fig. 1. (a) Relative delay for the single Lorentzian line (solid blue line), the double Lorentzian line (dashed red line for simulation, circles for experimental results), and the triple Lorentzian line (dotted magenta line for simulation, squares for experimental results) (b) Lorentzian line-center amplitude gain coefficients g_{01} (solid blue line), g_{02} (dashed red line), g_{t01} (dashed-dotted magenta line) and g_{t02} (dotted magenta line). The fitting gain coefficients extracted from the measured Brillouin gain spectra are represented by circles for the double Lorentzian line, and squares for the triple Lorentzian line (c) Normalized line separation for the double Lorentzian line (δ_2/γ, solid blue line) and the triple Lorentzian line (δ_3/γ, dashed red line).

The fraction of light directed to the Mach-Zehnder modulator EOM2 is employed for pump wave generation. In particular, pump wave is produced by driving EOM2 with a microwave frequency ν_B, while setting the dc bias voltage so that no light is transmitted in absence of a modulation signal (blocking state). In this way, the output light from EOM2 will consist of two sidebands having a frequency separation equal to twice the modulation frequency ν_B [20]. The band-pass optical filter OF is used to filter out one of these two sidebands, so as to achieve a monochromatic light at the input of EOM3. The modulation frequency ν_B is set to the Brillouin frequency shift of the slow light optical fiber ($\nu_B \approx 10.85$ GHz), so that the carrier frequency of the pulses produced by modulator EOM1 corresponds to the Stokes frequency of the fiber when using the light exiting from OF as the pump. When no rf signal is applied to the additional modulator EOM3, a monochromatic pump beam is then achieved for single gain line experiments. Instead, when applying a rf signal to EOM3, either a bichromatic or trichromatic pump beam is produced. In particular, a double Lorentzian line is produced by operating EOM3 around its blocking state, whereas a triplet results by biasing EOM3 away from its blocking state, so as to not suppress the pump wave carrier frequency. Hence, the selection between a bichromatic or trichromatic pump is operated in this set-up by simply adjusting the dc bias voltage of EOM3. The transfer function of the so-achieved slow light medium is then represented by Eq. (7) or Eq. (8), depending on the bias conditions of EOM3. When operating in a doublet configuration, the frequency distance between the two gain lines, $2\delta_2$, is equal to twice the rf tone applied to EOM3, whereas in a triplet configuration the three gain lines are equally-spaced, with a distance between two adjacent gain lines, δ_3, equal to the applied rf frequency. The above considerations are valid under the hypothesis that the peak-to-peak voltage of the rf signals applied to both EOM2 and EOM3 is so small that the higher-order sidebands produced by the process of intensity-modulation are negligible. The pump beam is amplified by an erbium-doped fiber amplifier (EDFA) and routed via circulator OC to pump a 8-km-long SMF-28 fiber (the slow light medium). For this fiber, an SBS linewidth (full-width at half-maximum) of $\gamma/\pi \approx 45$ MHz was measured. After passing through the slow light medium, the pump beam is blocked by the optical isolator OI.

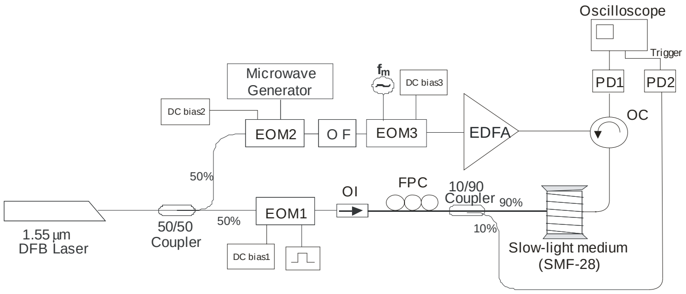

Fig. 2. Experimental set-up based on stimulated Brillouin scattering in optical fiber. OI: optical isolator; EOM1, EOM2, EOM3: Mach-Zehnder modulators; FPC: fiber polarization controller; OC: optical circulator; PD1, PD2: photodetectors; OF: optical filter; EDFA: Erbium-doped fiber amplifier; SMF-28: 8-km-long SMF fiber.

The optical pulses produced by EOM1 are approximately Gaussian-shaped and counter-propagate with respect to the pump beam in the fiber. The dc bias of EOM1 is regulated in order to minimize the baseline of the Stokes pulses (i.e. EOM1 is biased at its blocking state). A 10% fraction of the pulse energy is directed to the fast photodetector PD1, whose output is used as trigger for the digital oscilloscope. The slow light delayed and amplified pulses are routed via OC to a second photodetector PD2, whose output is directed to the oscilloscope.

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Finally, the fiber polarization controller FPC is used to maximize the SBS slow light delay experienced by the Stokes pulses.

For double-line and triple-line experiments, the best operating conditions can be extracted from Figs 1(b-c). In particular, we set the frequency f_m applied to EOM3 according to the value of δ_2 (double-line) or δ_3 (triple-line) given in Fig. 1(c), whereas the dc bias voltage of EOM3 and the EDFA gain were adjusted so as to achieve the gain coefficients given in Fig. 1(b). To ensure that the gain coefficients were tuned to the desired values provided by the optimization procedure, we performed Brillouin gain spectrum measurements by launching a weak continuous-wave probe signal into the fiber, counter-propagating with respect to the pump beam. The Brillouin gain spectrum was measured by sweeping the microwave frequency applied to EOM2 around the Brillouin frequency shift of the slow light fiber, and measuring the probe wave amplification over this frequency range. By numerically fitting the measured Brillouin gain spectrum to $\left|H_3(\omega)\right|^2$, the gain coefficients g_{t01} and g_{t02} of the implemented transfer function were retrieved. Note that, in the case of gain doublet experiments, the condition $g_{t01} = 0$ was easily fulfilled by adjusting the bias voltage applied to EOM3, until a minimum was found for the optical power entering the EDFA. For gain triplet experiments, and within the small-signal approximation, the control of the EDFA gain permitted to change both gain coefficients (g_{t01} and g_{t02}) without altering their ratio, whereas the latter was adjusted by only acting on the dc bias voltage of EOM3.

The first experiments were conducted for a gain doublet configuration. As in this case a bichromatic pump beam must be produced at the output of EOM3, we biased EOM3 around its blocking state. For each selected pulse bandwidth, we set the frequency of the rf signal applied to EOM3 according to Fig. 1(c), set the gain coefficient g_{02} according to Fig. 1(b), and measured the delay of the peak of the pulses induced by the slow light medium. The measured delays are represented by the circles in Fig. 1(a), and agree reasonably well with the numerical predictions. We also report, in Fig. 1(b), the gain coefficients g_{02} as resulted from Brillouin gain spectrum measurement and fitting.

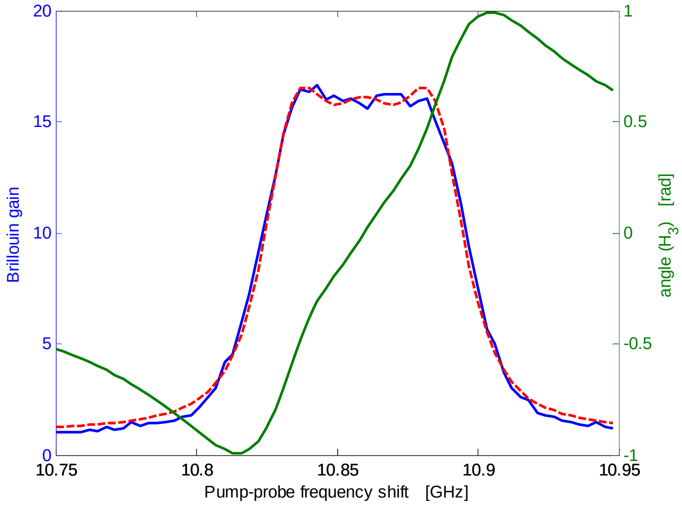

Fig. 3. Measurement (blue solid line) and numerical fit (red dashed line) of the Brillouin gain spectrum, related to a triple Lorentzian line configuration optimized for $\Delta_b/\gamma = 1.33$. The line separation δ_3 is 27 MHz, whereas the gain coefficients retrieved from fitting procedure are $g_{t01} = 0.59$ and $g_{t02} = 0.98$. The green line represents the phase of the transfer function H_3, calculated from Eq. (8) by using the above gain coefficients, and evaluated for z = 0.

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The next test was performed for a gain triplet configuration. We selected a pulse bandwidth for which the gain triplet configuration was expected to yield best results than those allowed by single-line and double-line configurations. In particular, we set $\Delta_b/\gamma = 1.33$ ($\tau \approx 18$ ns). For this measurement, we adjusted the EDGA gain, the dc bias voltage and rf signal applied to EOM3 so as to tune the slow light medium parameters to the optimal values reported in Figs. 1(a-c).

It is useful to show the Brillouin gain spectrum measured after that the different parameters were set to the optimal values (see Fig. 3). It can be noted how an opportune setting of the operation conditions of EOM3 (modulation frequency and dc bias voltage), results in a fairly uniform Brillouin gain and linear phase over a relatively large frequency range. This corresponds to the condition of low distortion for pulses having a bandwidth falling within this range. As a matter of fact, the distortion-constrained pulse delay measured in these new experimental conditions was ≈ 3.51 ns, a value that is almost twice the ≈ 1.84-ns distortion-constrained pulse delay measured in the gain doublet configuration and for the same pulse bandwidth

In order to better underline the benefit resulting from the use of the central gain line in conjunction with the two lateral lines, we performed another delay measurement in gain doublet configuration, in which the slow light medium parameters were modified with respect to the distortion-constrained values of Figs. 1(b-c). The selected pulse bandwidth was still $\Delta_b/\gamma = 1.33$. However, while the frequency applied to EOM2 was still set according to Fig. 1(c), the EDFA gain was increased until a pulse delay equal to the one achieved for the gain triplet configuration (3.51 ns) was reached. As a delay of 3.51 ns is higher than the maximum distortion-constrained delay allowed by the gain doublet configuration for the considered pulse bandwidth (see Fig. 1(a)), the amplitude gain coefficient for this measurement will be higher than the distortion-constrained gain of Fig. 1(b), so that some degree of pulse distortion is now expected. The temporal evolution of the delayed pulse, measured in these conditions, is compared in Fig. 4 with the delayed pulse previously achieved by using the gain triplet configuration. Actually, while the achieved delay is the same for the two configurations, it is seen that the delayed pulse in the case of bichromatic pump is slightly distorted with respect to the undelayed pulse. Actually, for a pulse bandwidth $\Delta_b/\gamma = 1.33$, half-line separation $\delta_2 = 2\pi \times 21.65$ MHz and a gain coefficient assuring a pulse delay of ≈ 3.5 ns ($g_{02} = 1.17$), we calculated an amplitude distortion $Da = 0.10$ and a phase distortion $Dp = 0.02$ by using Eqs. (4-5). Hence, the amplitude distortion exceeds in this case the limit imposed for the calculation of the parameters plotted in Figs. 1(a-c). Figure 4 also shows that the pulse measured in the case of gain triplet configuration has a shape which most closely resembles the shape of the undelayed pulse.

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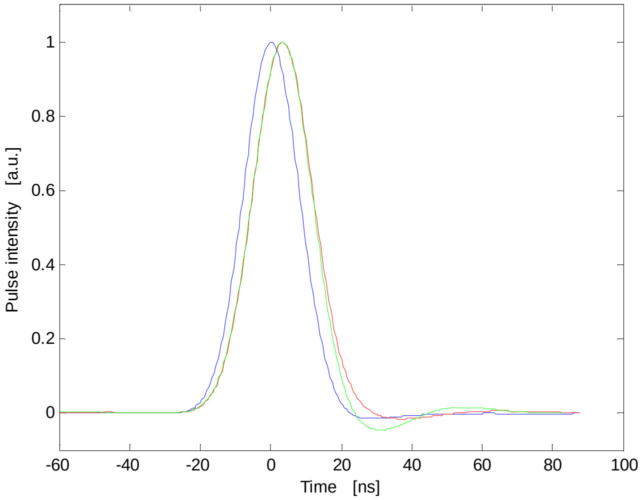

Fig. 4. Slow light delay induced by SBS in a single-mode optical fiber. The different curves represent the temporal evolution of the Stokes pulses emitted from the fiber in absence (blue line) of the pump beam, and in presence (red line and green line) of the pump beam. The green line refers to the case of a gain doublet configuration, with $\delta_2 = 2\pi \times 21.65$ MHz, whereas the red line refers to the case of a gain triplet configuration, with $\delta_3 = 2\pi \times 27$ MHz.

4. Conclusions

The distortion-management technique proposed in [13] has been applied to the case of a composite slow light medium constructed using three equally-spaced Lorentzian lines. It has been demonstrated that, by opportunely choosing the gain line frequency separation, the line-center gain of the central line and the line-center coefficients of the two lateral lines, it is possible to improve the slow light pulse delay with respect to the double gain configuration, while imposing a limit on the allowable pulse distortion and maximum gain. Experimental results have been presented, in which the Brillouin gain produced by a trichromatic pump beam is employed to delay Stokes pulses which counter-propagate along a single-mode optical fiber. While the improvement achieved by moving from a doublet configuration to a triplet configuration is less pronounced as the one achieved by moving from a single Lorentzian line to a Lorentzian doublet, it has been shown that a gain triplet can be realized in slow light systems exploiting Brillouin gain in optical fibers, by using the same experimental set-up employed for the gain doublet, without needing any additional electronic or optical devices. The proposed approach provides an operation pulse bandwidth which is in the order of twice the natural SBS gain bandwidth (see Fig. 1(a)), allowing for useful data rates of a few tens Mb/s. Although such a bandwidth is much less than the one recently achieved by direct current modulation of a DFB laser [16], the results presented in this paper are mainly intended to be a further demonstration of the capabilities of distortion management, in optimizing the design of a slow light medium. Moreover, the presented results suggest that the use of more complex modulation schemes for the optical pump beam (e.g., phase modulation), may further enhance the maximum distortion-constrained relative delay in SBS-based slow light systems.

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