Optical Fiber Technology 16 (2010) 12–16

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Numerical investigation of system performance in SBS slow light using filtered incoherent pump

D. Zheng, W. Pan, B. Luo, N. Jiang, A. Yi, J. Ye, L.-S. Yan *

Center for Information Photonics & Communications, School of Information Science & Technology, Southwest Jiaotong University, Chengdu, Sichuan 610031, China

ARTICLE INFO

Article history:
Received 29 June 2009
Revised 14 August 2009
Available online 25 October 2009

Keywords:
Slow light
Stimulated Brillouin scattering
Incoherent pump
SBS gain spectrum

ABSTRACT

Slow light based tunable delay line has been a potential enabler for all-optical networks. We numerically investigate the transmission performance incorporating the signal bandwidths into the incoherently pumped stimulated Brillouin scattering (SBS) slow light systems. Both the gain and loss part of the SBS spectrum are taken into account for more accurate comparison. Simulation results are illustrated in terms of the normalized delay and signal Q-factor products for both 2.5-Gb/s and 10-Gb/s on–off-keying (OOK) transmission systems. Optimization guidelines are given under different circumstances.
© 2009 Elsevier Inc. All rights reserved.

1. Introduction

Slow light and its applications into nonlinear signal processing have gained substantial interests [1–10] since the first few demonstrations [1–3]. One of the major applications for slow light is to generate tunable delays in advanced optical networks, especially through stimulated Brillouin scattering (SBS) in optical fiber itself [4–7], as elements based on such mechanism are promising candidates in high-speed all-optical networks and signal processing applications.

As pointed out and investigated to some extend, there are two major issues when adopting SBS based tunable delay elements into real systems: (i) the limited intrinsic bandwidth of SBS gain spectrum (typically tens of MHz), which is much narrower than the requirement to accommodate current high data rate signals (generally more than Gbit/s); (ii) signal distortions passing through the slow light element, resulting from the gain spectrum limitations and the slow light mechanism itself (e.g. pattern dependence [12] or pulse broadening).

To solve the first problem, researchers have proposed different schemes to increase the gain bandwidth to tens of GHz, including directly modulating the pump laser using pulse train [13]; pseudo-random bit sequence (PRBS) [14] or Gaussian noise [6]; external phase modulation [11,15,16]; multiple pump lines [17–19]. Related approaches are based on modulating coherent pump sources or modulators following the coherent sources. Therefore, for a multiple-channel system, each channel needs such a source; the configuration would be somewhat complicated. It was noted recently that incoherent pump source can be used to provide possible cost-effective solutions in multiple-channel systems through sharing the same incoherent pump source, although individual high power amplification is still required for each channel [20].

Regarding the signal distortion through slow light element, investigations are mostly dealing with characteristics of a single pulse in theory or typical experimental demonstrations in real transmission systems under preferred experimental parameters [21,22]. Moreover, since the SBS spectrum includes both the gain and the loss part, signals transmitted at higher data rate (i.e. corresponding to wider spectrum) might be further degraded when the loss part of the SBS gain spectrum is getting involved. Such system evaluation has not been performed yet. Therefore, it would be desirable to investigate the performance of SBS slow light systems in a more complete way to provide useful design guidelines under a more general parameter set.

In this paper, we build a complete SBS slow light transmission system model and simulate related performance. Here we use an optical filter to slice the spectrum of an incoherent source (e.g. an amplified spontaneous emission – ASE source) to act as the SBS pump source. As pointed, phase information of the data stream can be well preserved through the slow light (e.g. differential phase-shift-keying, DPSK [7]) or well-proved trend between the generated delay and the number of – ary exists for multi-level (or M-ary) phase-modulated data [22], thus we concentrate on the transmission performance of the on–off-keying (OOK, including both return-to-zero and non-return-to-zero, i.e. RZ and NRZ) data formats.

As we vary the bandwidth of the pump source, corresponding to the bandwidth of the optical filter, the performance is evaluated in

* Corresponding author.
E-mail address: lsyan@home.swjtu.edu.cn (L.-S. Yan).

1068-5200/$ - see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.yofte.2009.09.006

terms of the normalized delay and signal Q-factor product. In addition to data formats, both the pump power and the transmission data rate are incorporated: the pump profile and power can change the profile and peak of the gain spectrum, respectively, as well as the loss part of the spectrum, and consequently may affect the signal quality at higher data rate (i.e. wider spectrum). We find that the optimized and normalized parameter, defined as the bandwidth of the pump-slicing over the signal data rate, varies at different pump power levels, as well as different data formats. Therefore, related results can be used as design guidelines for real systems.

2. Coherent vs. incoherent pumped SBS

In principle, slow light can be achieved by the creation of a large normal dispersion of the refractive index in a nonlinear medium. Large normal dispersion gives rise to an increase in the group index, $n_g(\omega_0) = n(\omega_0) + \omega_0 (dn/d\omega)$, where ω_0 is the carrier frequency of the optical pulse and $n(\omega_0)$ is the refractive index of the medium. Therefore the group velocity $v_g = c/n_g$ can be altered and a controllable group delay is obtained for the signal. In particular, the process of SBS slow light is based on the interaction between two counter-propagated beams inside optical fiber itself: the pump light and the signal. When the pump is strong enough, and frequencies of the pump light ω_p and the signal ω_s meet a certain criteria, acoustic wave will be generated. The signal will be amplified within a narrow bandwidth (typically tens of MHz). More importantly, the SBS-induced amplifying resonance accompanies a strong change in the group velocity within a narrow bandwidth, which in turn introduces an additional delay of the pulse ($\Delta\tau$).

As mentioned, in order to increase the gain spectrum to GHz so that the slow light element can accommodate Gbit/s data signal, researchers mostly use the configuration shown in Fig. 1a. The coherent source is modulated through PRBS or Gaussian noise, or just through an external phase modulator (PM). For a multiple-channel system, each channel needs such a modulated source, and the SBS gain spectrum is hard to control due to the random nature of frequency modulation. On the other hand, if we use an incoherent source, e.g. an ASE source, followed by a periodic optical filter (e.g. a Fabry–Perot type one), we can obtain multiple pump lines and then can use each line for individual channels (Fig. 1b). Since generally the output of such source is not high enough, high power optical amplifier is still required for each pump lines, similar to conventional coherent approaches. As the bandwidths of optical filters are generally more than GHz or even wider, the SBS gain spectrum will be wider enough for most applications. The SBS gain spectra are easy to tailor by properly choosing the shape and bandwidth of the spectral-slicing filter. Such configuration may provide relatively simple solutions for future wavelength-division-multiplexing (WDM) systems, although the overall performance of such systems may not be as good as conventional approaches depending on the noise reduction ability of optical filters.

3. Simulation model

The simulated system setup is shown in Fig. 2a, where the SBS pump is based on a polarized and spectrally sliced ASE source (as the SBS slow light process is polarization sensitive), with its bandwidth determined by the optical filter (bandpass filters such as fiber-Bragg-grating, Fabry–Perot, arrayed-waveguide-grating, can be used here). The high power EDFA is used to provide a certain pump power (P_{pump} in mW) to generate SBS slow light effect in the highly nonlinear fiber (HNLF). The length of the HNLF is set to 2-km, with its typical specifications similar to [22], some in

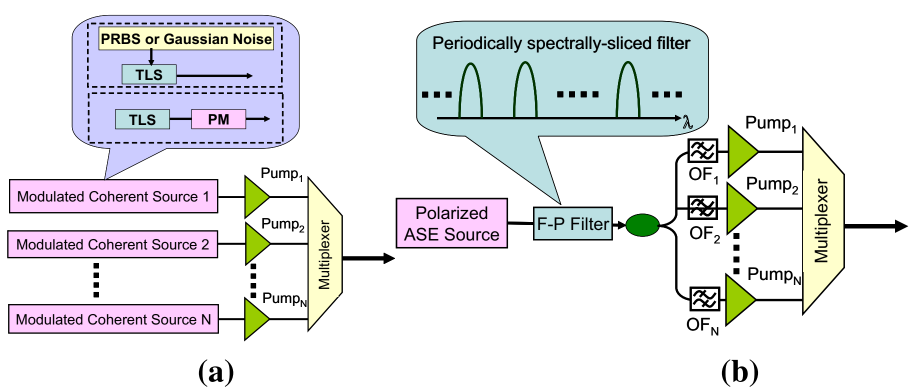

Fig. 1. Illustration of typical configurations for a multiple-channel system when using (a) coherent pump source (TLS: tunable light source, PM: phase modulator) (b) incoherent (here an ASE) source (F–P: Fabry–Perot, OF: optical filter).

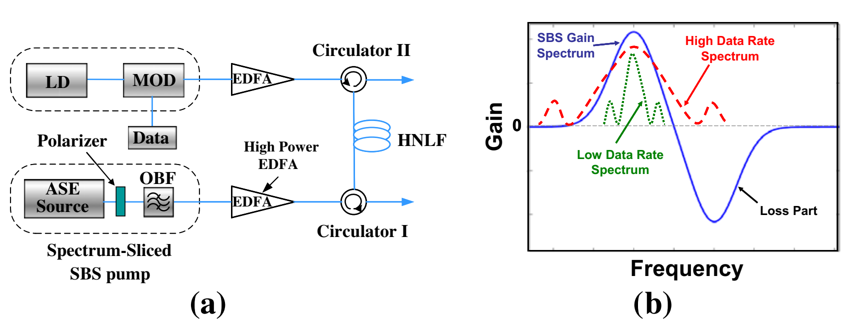

Fig. 2. Simulation model: (a) System setup of SBS slow light based on spectrally-sliced incoherent pump (MOD: modulator, OBF: optical bandpass filter, HNLF: Highly nonlinear fiber). (b) Illustration of the relationship among the broadened SBS spectrum (including the loss part), the spectrum of low data rate signal (e.g. 2.5-Gb/s) and the spectrum of high data rate signal (e.g. 10-Gb/s).

[6]. OOK data sequences (NRZ and RZ) are generated using electro-optic modulators (MOD) and propagate through the slow light section, counter-propagating inside the HNLF with respect to the spectrally-sliced incoherent pump. The amplified and delayed signal is then routed out via circulator I. Unwanted pump is routed out via circulator II. Other parameters include the effective mode area $A_{eff} = 14.5\ \mu m^2$, the dispersion slope is 0.045 ps/(nm^2 km), and the gamma coefficient is 9.1 W^{-1} km^{-1}, the gain coefficient of the center $g_0 = 5 \times 10^{-11}$ m/W, the intrinsic gain bandwidth $\Gamma_B/2\pi = 40$ MHz, and the refractive index of the fiber $n = 1.45$.

Considering the data rate of the transmission system, we illustrate the relative relationships between the SBS gain spectrum and the data spectrum shown in Fig. 2b. Low data rate signals can be transparent to the SBS gain spectrum, while at high data rate, part of the data spectrum may fall into the loss part of the SBS spectrum, thus introducing additional degradations. In addition, since the phase information is useless for the incoherent pump source, the complex gain spectrum $g(\omega)$ is simulated using the convolution of the intrinsic SBS gain spectrum $\bar{g}_0(\omega)$ and the power spectrum of the pump field $I_p(\omega_p)$ [6]. The pump source is considered to exhibit a Gaussian-type power spectrum as the polarized ASE source passing through the optical filter.

4. Simulation results

Starting from the low data rate, i.e. 2.5-Gb/s, we simulate the performance variation as we vary the bandwidth of the optical filter. As defined in [7], the slow light bandwidth is normalized by signal bit rate, and the pulse delay is normalized by the bit time (i.e. normalized delay), Figure of merit (FOM) is defined as the product of the normalized delay and signal Q-factor. The Q-factor is defined as $Q = (P_1 - P_0)/(\sigma_1 + \sigma_0)$, where P_1 and P_0 are the mean of 1 and 0 at the maximum eye opening instant; σ_1 and σ_0 are the standard deviations for levels 1 and 0, respectively. The pulse delay is defined as the time shift at the maximum power level in the simulation.

First we show simulated results of generated delay vs. pump power at different bandwidths (or full-width at half-maximum, FWHM) in Fig. 3 for the 2.5-Gb/s NRZ and RZ formats. As expected, the generated delay increases as the pump power increases, while narrower bandwidth of the sliced pump corresponds to larger delay under the same pump power. Some individual results agree well with available experimental points under similar conditions [7]. It is also noted that as the spectral width of the NRZ signal is narrower than that of the RZ signal, most of frequency components of NRZ signal are closer to the delay peak. Subsequently the generated delay of NRZ signal is larger than that of RZ signal under the same pump condition.

In addition, typical eye diagrams of both data formats are shown in Fig. 4, where FWHM of the optical filter is set to 4 GHz and the optical signal-to-noise-ratio (OSNR) is set to 25 dB, where the noise is modeled as Gaussian white noise. Note that pulse broadening does exist (especially the RZ signal) and should be considered as a major challenge for future performance improvement.

More importantly, the relationships between FOMs and the slow light bandwidths are shown in Fig. 5a and b for 2.5-Gb/s NRZ and RZ data formats, respectively. As the pump power increases, the optimized slow light bandwidth also shifts from lower values to higher ones. As the pump power higher than 300 mW,

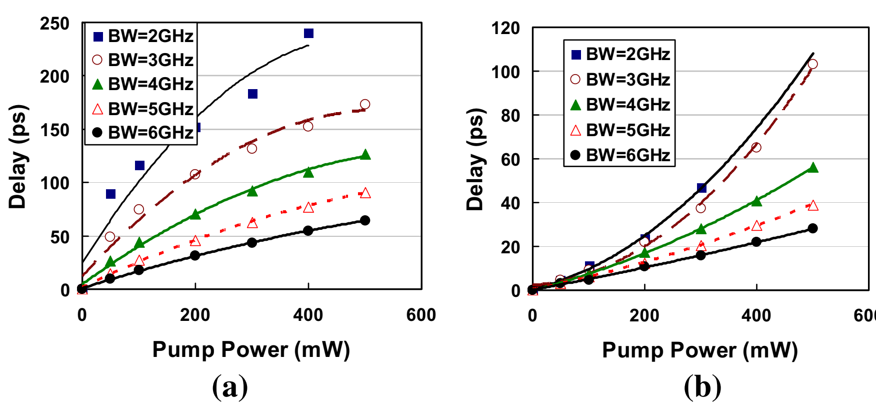

Fig. 3. Generated 2.5-Gb/s OOK signal delay vs. pump power at different pump-slicing bandwidths: (a) NRZ data (b) RZ data.

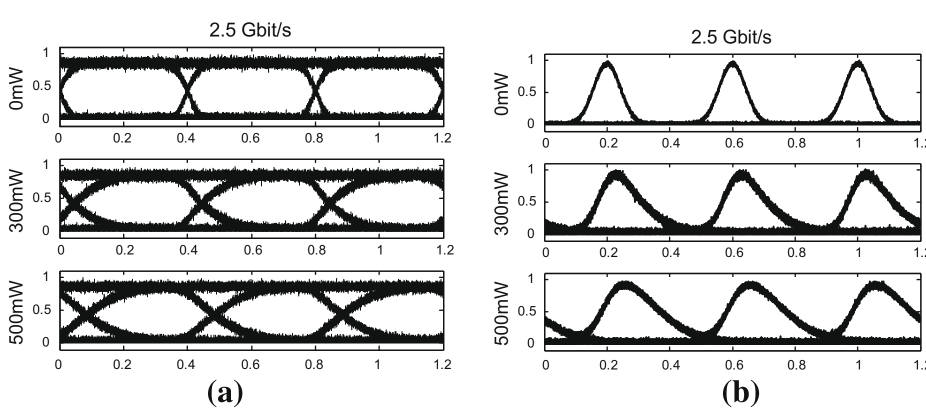

Fig. 4. Typical 2.5-Gb/s eye diagrams after slow light under different pump power levels (a) NRZ; (b) RZ. Here the FWHM of the optical filter is set to 4-GHz, and the OSNR of the signal is set to 25 dB.

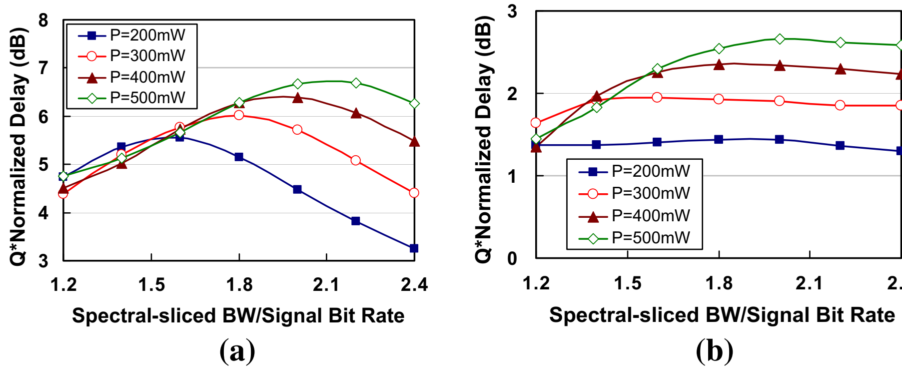

Fig. 5. Figure of merits (FOMs) vs. slow light bandwidths at different pump power levels for 2.5-Gb/s OOK signals (highlighted solid lines showing the trends of optimized points): (a) NRZ data (b) RZ data.

the optimized slow light bandwidth is between 1.8 and 2.0 times the signal bandwidth for NRZ signal, while the optimized value keeps relatively constant (i.e. >1.6) for the RZ signal.

When the data rate increases to 10-Gb/s, we would expect that the loss part of the SBS gain spectrum will have certain effects on the signal transmission. Similar to the 2.5-Gb/s case, the trends among the signal delay, the pump power and the slicing bandwidth still stand for the 10-Gb/s case (Fig. 6), although the generated delay is much less than that of 2.5-Gb/s due to higher data rate. The corresponding eye diagrams are also shown in Fig. 7, illustrating the similar behavior as 2.5-Gb/s. As expected, the performances between two data rates are different due to the limited bandwidth of the gain spectrum, while such differences are not that substantial mainly due to the fact: the majority of frequency components of the signal still fall into the center of the gain spectrum; only limited high frequency components may fall into the loss part.

In addition, NRZ data generates larger delay than the RZ signal under the same condition. This is because that the spectral width of NRZ signal is narrower than that of RZ signal, so the frequency components of NRZ signal are closer to the gain peak. The linear regime (delay vs. pump power) does exist for low pump power, while

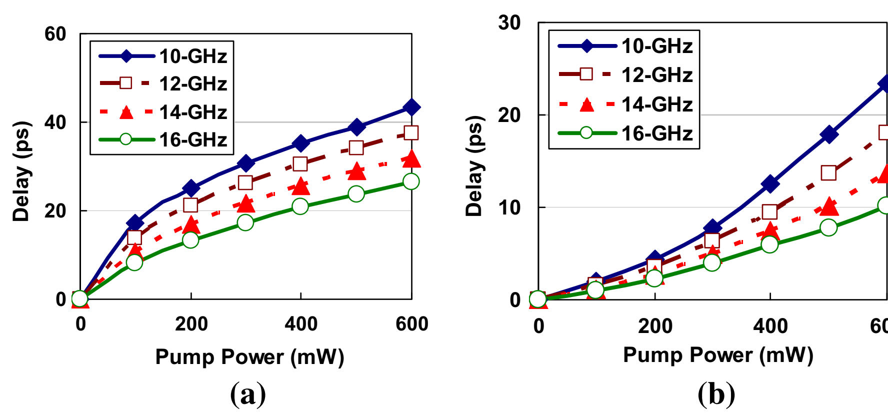

Fig. 6. Generated 10-Gb/s OOK signal delay vs. pump power at different pump-slicing bandwidths: (a) NRZ data (b) RZ data.

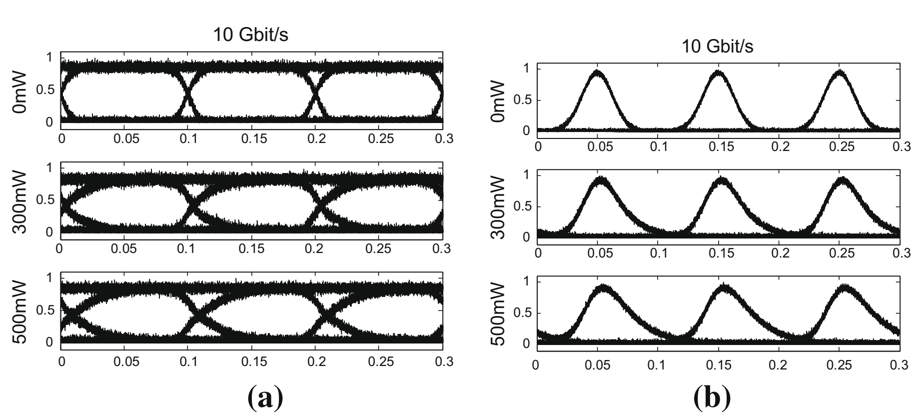

Fig. 7. Typical 10-Gb/s eye diagrams after slow light under different pump power levels (a) NRZ; (b) RZ. Here the FWHM of the optical filter is set to 12-GHz, and the OSNR of the signal is set to 25 dB.

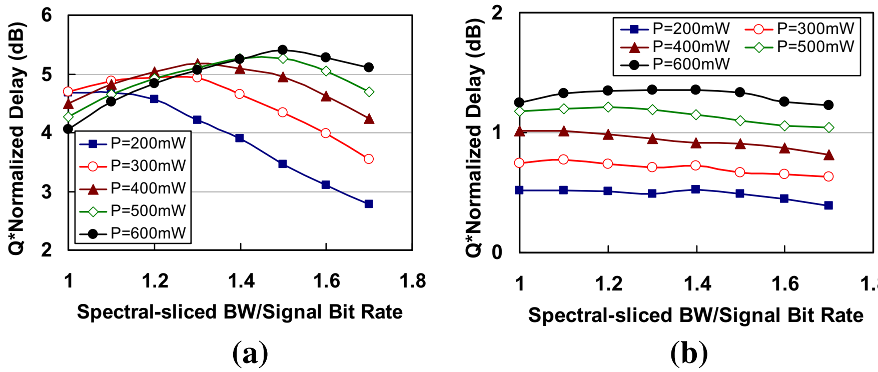

Fig. 8. Figure of merits (FOMs) vs. slow light bandwidths at different pump power levels for 10-Gb/s OOK signals: (a) NRZ data (b) RZ data.

at higher pump power, the signal distortion becomes more serious, the relationship between the delay and pump power turns to be nonlinear [17]. As we evaluate the delay for RZ signal using the peak power of the pulse, while the width of 98% peak values for NRZ signal, the tendency of RZ is quite different from the NRZ one. It is noted that there is still no accurate method to measure the delay for NRZ signal, especially when the signal is distorted (i.e. the rise/fall time is quite asymmetric).

On the other hand, Fig. 8 shows the FOM vs. the slow light bandwidth at different pump power levels. Now unlike the 2.5-Gb/s case, at a given pump power, the optimized slow light bandwidths is between 1.2 and 1.4 times the signal bandwidths for 10-Gb/s NRZ. While for the RZ data, due to its even wider spectrum, the optimized bandwidth relationship keeps almost flat. While it should be noted that due to the loss part involvement, the FOM values of both RZ and NRZ at 10-Gb/s are lower than those at 2.5-Gb/s data rate, especially for the RZ signal. As an example, the FOM can be more than 2.5 for 2.5-Gb/s under 500 mW pump power, while it only can be as high as 1.1–1.2 when the data rate increases to 10-Gb/s. Such significant degradation is mainly due to the contribution of the loss part of the SBS gain spectrum. Therefore, it would be good to avoid or at least mitigate the effect of the loss part through different ways [19], which is also one of our next goals.

5. Conclusion

In conclusion, we investigated the SBS slow light system performance under different scenarios, when spectrally-sliced incoherent pump source is used. Parameters such as the pump power, the slow light bandwidth and the FOM, are all incorporated into simulation models. Optimized design guidelines are provided for both 2.5-Gb/s and 10-Gb/s OOK signals, indicating that the bandwidth of the sliced pump should be carefully selected according to the transmission data rate and the SBS pump power.

Acknowledgments

The research is supported by Program for New Century Excellent Talents in University (NCET-08-0821), Ministry of Education, China, the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry, and the State Key Laboratory of Advanced Optical Communication Systems and Networks, China. The authors would also like to thank Dr. Bo Zhang, Lin Zhang and Prof. Alan Willner at University of Southern California for helpful discussions and encouragement.

References

[1] M.S. Bigelow, N.N. Lepeshkin, R.W. Boyd, Superluminal, slow light propagation in a room-temperature solid, Science 301 (2003) 200.
[2] B. Macke, B. Segard, Propagation of light-pulses at a negative group-velocity, Eur. Phys. J. D. 23 (2003) 125–141.
[3] R.W. Boyd, D.J. Gauthier, Slow and fast light, in: E. Wolf (Ed.), Progress in Optics, vol. 43, Elsevier, Amsterdam, 2002, pp. 497–530 (Chapter 6).
[4] Y. Okawachi, M.S. Bigelow, J.E. Sharping, Z. Zhu, A. Schweinsberg, D.J. Gauthier, R.W. Boyd, A.L. Gaeta, Tunable all-optical delays via Brillouin slow light in an optical fiber, Phys. Rev. Lett. 94 (2005) 153902.
[5] K.-Y. Song, M.G. Herraez, L. Thevenaz, Observation of pulse delaying and advancement in optical fibers using stimulated Brillouin scattering, Opt. Express 13 (2005) 82–88.
[6] Z. Zhu, A.M.C. Dawes, D.J. Gauthier, L. Zhang, A.E. Willner, Broadband SBS slow light in an optical fiber, J. Lightwave Technol. 25 (2007) 201–206.
[7] A.E. Willner, B. Zhang, L. Zhang, L.-S. Yan, I. Fazal, Optical signal processing using tunable delay elements based on slow light, J. Sel. Top. Quant. Electron. 14 (2008) 691–705.
[8] X. Zhao, P. Palinginis, B. Pesala, C. Chang-Hasnain, P. Hemmer, Tunable ultraslow light in vertical-cavity surface-emitting laser amplifier, Opt. Express 13 (2005) 7899–7904.
[9] Liu Fangfei, Li Qiang, Zhang Ziyang, Qiu Min, Su Yikai, Optically tunable delay line in silicon micro ring resonator based on thermal nonlinear effect, J. Sel. Top. Quant. Electron. 14 (2008) 706–712.
[10] L. Yi, W. Hu, Y. Su, M. Gao, L. Leng, Design and system demonstration of a tunable slow-light delay line based on fiber parametric process, IEEE Photonics Technol. Lett. 18 (2006) 2575–2577.
[11] L. Yi, L. Zhan, W. Hu, Y. Xia, Delay of broadband signals using slow light in stimulated Brillouin scattering with phase-modulated pump, IEEE Photonics Technol. Lett. 19 (2007) 619–621.
[12] L. Zhang, T. Luo, C. Yu, W. Zhang, A.E. Willner, Pattern dependence of data distortion in slow-light elements, J. Lightwave Technol. 25 (2007) 1754–1760.
[13] V.P. Kalosha, L. Chen, X. Bao, Slow and fast light via SBS in optical fibers for short pulses and broadband pump, Opt. Express 14 (2006) 12693–12703.
[14] M.G. Herráez, K.Y. Song, L. Thévenaz, Arbitrary-bandwidth Brillouin slow light in optical fibers, Opt. Express 14 (2006) 1395–1400.
[15] Z. Liu, Y. Dong, Q. Li, Slow light in multi-line Brillouin gain spectrum, Opt. Express 15 (2007) 1871–1877.
[16] R. Pant, M.D. Stenner, M.A. Neifeld, Z. Shi, R.W. Boyd, D.J. Gauthier, Maximizing the opening of eye diagram for slow-light systems, Appl. Opt. 46 (26) (2007) 6513–6519.
[17] Z. Shi, R. Pant, Z. Zhu, M.D. Stenner, M.A. Neifeld, D.J. Gauthier, R.W. Boyd, Design of a tunable time-delay element using multiple gain lines for increased fractional delay with high data fidelity, Opt. Lett. 32 (14) (2007) 1986–1988.
[18] M.D. Stenner, M.A. Neifeld, Z. Zhu, A.M.C. Dawes, D.J. Gauthier, Distortion management in slow-light pulse delay, Opt. Express 13 (25) (2005) 9995–10002.
[19] K.-Y. Song, K. Hoate, 25 GHz bandwidth Brillouin slow light in optical fibers, Opt. Lett. 32 (3) (2007) 217–219.
[20] B. Zhang, L.-S. Yan, L. Zhang, A.E. Willner, Multi-channel SBS slow light using spectrally-sliced incoherent pump, J. Lightwave Technol. 26 (23) (2008) 3763–3769.
[21] L. Yi, Y. Jaouën, W. Hu, J. Zhou, Y. Su, E. Pincemin, Simultaneous demodulation and slow light of differential phase-shift keying signals using stimulated-Brillouin-scattering-based optical filtering in fiber, Opt. Lett. 32 (2007) 3182–3184.
[22] B. Zhang, L.-S. Yan, L. Zhang, S. Nuccio, L. Christen, T. Wu, A.E. Willner, Spectrally-efficient slow light using multi-level phase-modulated formats, Opt. Lett. 33 (2) (2008) 55–57.