2009-01-01

Zero-Broadening Measurement in Brillouin Based Slow-Light Delays

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Recommended Citation

Wiatrek, A. et al. (2009) Zero-Broadening Measurement in Brillouin Based Slow-Light Delays. *Optics Express*, vol. 17, no. 2, pp.797-802 doi:10.1364/OE.17.000797

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Zero-broadening measurement in Brillouin based slow-light delays

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Abstract: A novel method for the achievement of zero-broadening in a SBS based slow-light system is discussed in theory and demonstrated experimentally. The system is realized just with a single broadened Brillouin gain. It is shown, that if the gain bandwidth is much broader than the initial pulse width, the output pulse width decreases with increasing pump power. A compression of approximately 90 % of the initial pulse width was achieved in simulation and experiment.

OCIS codes: (999.9999) Slow light; (290.5900) Scattering, stimulated Brillouin; (060.4370) Nonlinear optics, fibers; (000.4430) Numerical approximation and analysis.

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1. Introduction

The alteration of the group velocity of optical pulses in fibers by so called slow-light systems is a promising technique for future communication networks. With all optical signal processing such as optical data synchronization and optical buffers it would be possible to overcome the speed limitations of todays networks. Therefore, over the last years many rigorous studies were performed on achieving an optically controlled tunable pulse delay at high delay times [1–5]. The nonlinear optical effect of stimulated Brillouin scattering (SBS) became important for fiber based slow-light systems, because of its apparent advantages; working in the whole transparency range of every fiber, high delay times at small pump powers and easy implementation in existing communication networks. Drawbacks are the narrow bandwidth and the delay limiting factor of the saturation effect of SBS. Since high time delays are often accompanied with a strong pulse broadening, recent investigations are additionally focused on an optimal slow-light system design at low pulse distortions [6–9]. Initial theoretical investigations on zero-broadening in SBS based slow-light systems were presented in [10]. The first practical proof of the opportunity of zero-broadening slow-light was given in [11], where a gain was superimposed with two losses at its spectral boundaries.

Here we will show in simulation and experiment, that zero-broadening is possible even for a SBS based slow-light system consisting of a single gain line.

2. Theory

In Brillouin scattering a strong pump wave in a medium induces an electrostrictive acoustic wave which propagates in the pump wave's direction. Because of the relative velocity between the pump and the acoustic wave, the backscattered Stokes wave is down shifted in frequency, the so called Brillouin shift. A counter propagating signal wave at the Stokes wave's frequency is amplified by the pump wave. Besides the amplification, the phase of the signal wave is changed due to the SBS. According to the Kramers-Kronig relations pulses are slowed down inside the gain bandwidth [11]. A slow-light system consisting of a signal wave and a pump wave propagating in a fiber as Brillouin medium can be described by [12, 13]:

$$\begin{aligned}\frac{\partial E_S}{\partial z} &= -\left(\frac{g_B}{2A_{eff}}\Delta k_{eR}P_P - \frac{\alpha}{2}\right)E_S + j\cdot\left(\frac{g_B}{2A_{eff}}\Delta k_{eI}P_P + \gamma P_S\right)E_S \\ \frac{\partial E_P}{\partial z} &= -\left(\frac{g_B}{2A_{eff}}\Delta k_{eR}P_S + \frac{\alpha}{2}\right)E_P, \qquad (1)\end{aligned}$$

where E_S and E_P are the electric field components of the signal and the pump wave and P_S and P_P are the corresponding powers. A_{eff} is the effective core area, α is the fiber attenuation, γ is the nonlinear coefficient and g_B stands for the SBS gain coefficient. The phase mismatch terms Δk_{eR} and Δk_{eI} describe the gain distribution and the phase development according to the SBS. Since we use a cw-pump wave, we neglected the cross phase modulation and all terms regarding the pump wave's phase. For our measurement, a pump field more than ten times broader than the natural SBS gain bandwidth is used. Hence, following [7] the resultant SBS gain spectrum is approximately equal to the pump spectrum and hence, in case of a Gaussian shaped pump power spectrum the phase mismatch terms can be written as:

$$\Delta k_{eR} = \exp\left[-\ln(2)\left(\frac{\omega-\omega_0}{\Gamma}\right)^2\right] \qquad (2)$$

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$$\Delta k_{eI} = -j\exp\left[-\ln(2)\left(\frac{\omega-\omega_0}{\Gamma}\right)^2\right]\times\mathrm{erf}\left[j\sqrt{\ln(2)}\,\frac{\omega-\omega_0}{\Gamma}\right], \tag{3}$$

with ω_0 as the line center frequency and Γ as the half width at the half maximum bandwidth of the gain distribution.

3. Simulation

The differential equation system (DES) in Eq. (1) is numerically solved by a Runge-Kutta method. A shooting algorithm transforms the given boundary value problem into an initial value problem, which is easier to solve. The Fourier transform of a Gaussian Pulse with a full width at the half maximum (FWHM) of 1.5 ns and an amplitude of 2 μW defines the vector of boundary values for the shooting procedure. Hence, all spectral components of the pulse are calculated independently for a fiber length of 10 km. Due to the Runge-Kutta algorithm, effects such as the saturation of the pump are considered.

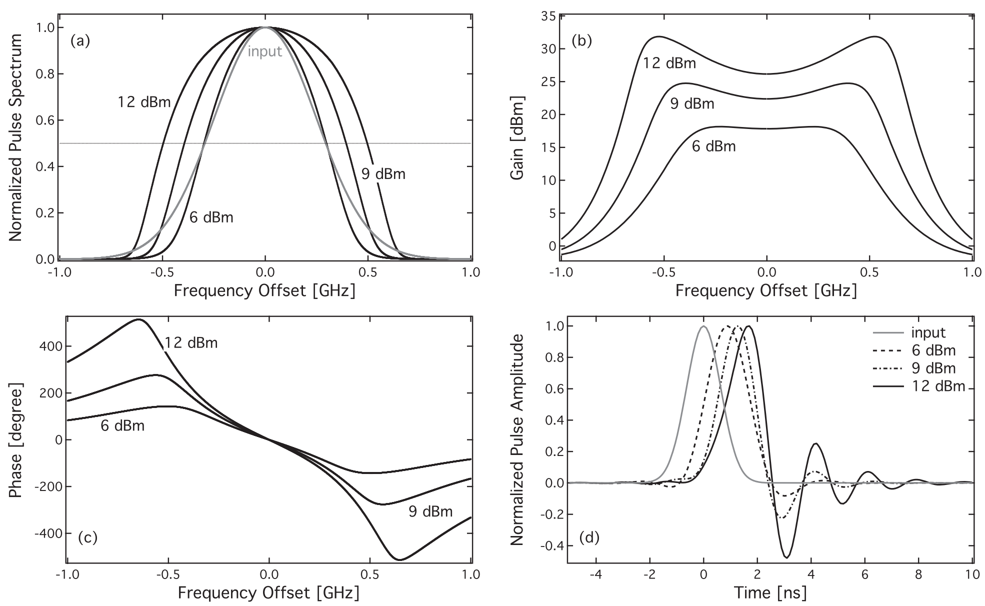

Fig. 1. Normalized pulse spectra (a), gain spectra (b), phase response spectra (c) and normalized pulse amplitudes (d) at different pump powers and with reference to initial temporal pulse and initial pulse spectrum.

In Fig. 1(a) the development of the pulse spectrum for different pump powers is shown for the special case of a gain FWHM bandwidth of 850 MHz. The center frequency components of the pulse spectrum are saturated, while the spectral boundaries are further amplified. Hence, the pulse spectrum is distorted in a way, that the FWHM bandwidth of the pulse spectrum increases with the pump power. Figure 1(b) shows the corresponding gain spectra and in Fig. 1(c) the phase spectral response of the slow-light system at different pump powers is shown. Due to the quasi linearity of the phase responses inside the FWHM bandwidth of the pulse spectra, little distortion and broadening by phase is assumed [9]. However, according to the relations between the frequency and the time domain, the increase of the FWHM bandwidth leads to a decrease of the temporal FWHM width of the pulse (Fig. 1(d)). But the temporal compression comes at the expense of a distorted pulse shape, i.e. ringing in Fig. 1(d).

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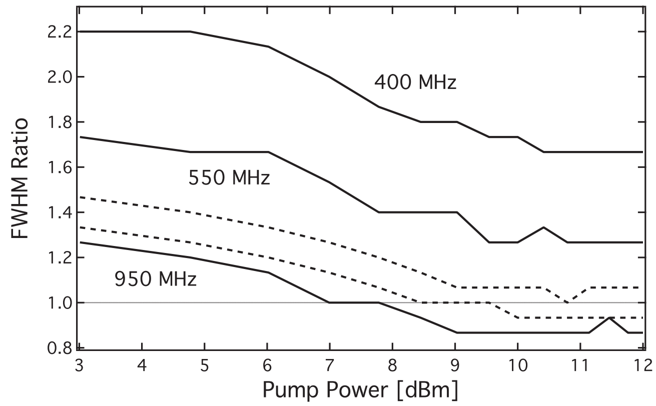

Fig. 2. FWHM ratio as a function of the pump power at different gain bandwidths (400 MHz, 550 MHz, 700 MHz, 850 MHz, and 950 MHz).

The results for the FWHM ratio of the initial pulse to the slow-light system output pulse as a function of the pump power at different gain FWHM bandwidths are shown in Fig. 2. The simulated 1.5 ns pulse has a FWHM bandwidth of approximately 600 MHz. Although the output pulse width decreases for all simulated gain bandwidths with increasing pump power, zero-broadening can only be achieved, if the gain bandwidth exceeds the initial pulse bandwidth. In this simulation the pulse is compressed to approximately 90 % of its initial value.

Considering the spectral narrowing and therefore temporal pulse broadening in SBS based slow-light systems, this method can be used to mitigate broadening effects. In a final section the attenuated spectral boundary components would be amplified according to Fig. 1(a). Because of this spectral reshaping effect, distortions in the frequency domain were very small. Therefore, the pulse shape and the pulse width could almost be held at the initial values for a very large time delay.

4. Experiment

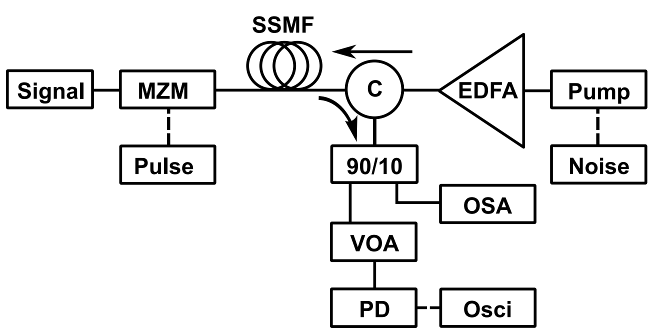

Fig. 3. Experimental setup. MZM: Mach-Zehnder modulator, SSMF: standard single mode fiber, C: circulator, EDFA: Erbium doped fiber amplifier, VOA: variable optical attenuator, PD: photodiode, OSA: optical spectrum analyzer, Osci: oscilloscope.

The experimental setup is shown in Fig. 3. A cw-signal laser is externally modulated by a Mach-Zehnder modulator. The generated pulse with a FWHM width of approximately 1.3 ns is coupled into a 10 km SSMF. A cw-pump, directly modulated by a noise signal for broadening,

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is amplified by an Erbium doped fiber amplifier (EDFA) and coupled into the opposite end of the fiber via a circulator. The tuned frequency difference between the pump and the signal wave is equal to the Brillouin shift frequency and monitored with an optical spectrum analyzer (OSA). Due to the SBS, the pulse is amplified and delayed by the pump wave. The pulse is detected by a photodiode and the electrical signal is measured with an oscilloscope (Osci). To prevent the photodiode from damage, a variable optical attenuator (VOA) with a power tracking function is used, which maintained the detector optical input power at -5 dBm. The pump power was measured by an optical power meter at the connection between circulator and SSMF.

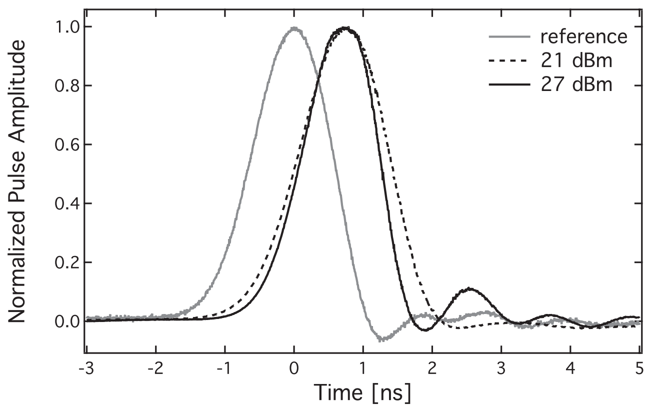

Fig. 4. Pulse evolution in comparison to the fiber output reference pulse.

Following the simulation results all measurements are made near to the saturation regime of the slow-light system. The reference pulse is not the fiber input pulse, but the output pulse without any SBS activity. However, in the case of a 10 km fiber, a 1.3 ns pulse and a small pulse power, the input and output pulse shapes are almost the same, neglecting the fiber attenuation. As an example Fig. 4 shows the output pulses in comparison to the reference pulse for two EDFA adjustments at a FWHM SBS gain bandwidth of 830 MHz. The compression effect and the slight pulse distortion follow the simulation predictions in Fig. 1(d). However, the distortion, i.e. the ringing, is lower than in simulation. A possible explanation for this difference is the nonideal Gaussian shape of the measured reference pulse. The slight distortion at the trailing edge of the reference pulse seems to mitigate the distortions due to the compression effect at higher pump powers.

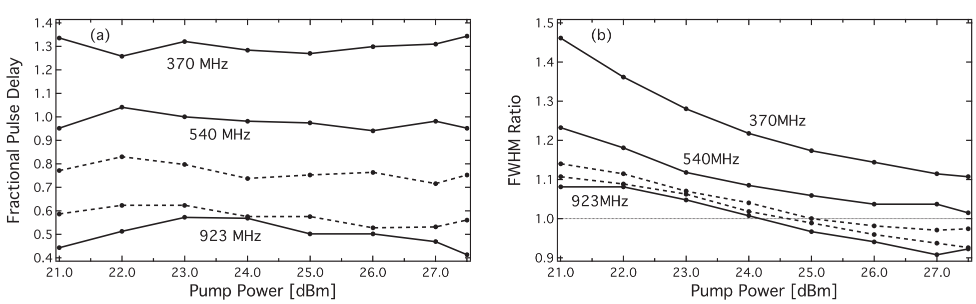

Fig. 5. Fractional pulse delay (a) and FWHM ratio (b) as a function of the pump power at different gain bandwidths (370 MHz, 540 MHz, 700 MHz, 830 MHz, and 923 MHz).

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In Fig. 5(a) the fractional time delay – the ratio of the pulse delay to the reference pulse width – as a function of the pump power for different gain bandwidths is shown. Following the theoretical investigations in [7] the delay time decreases with an increasing gain bandwidth. While the time delay in the small signal range increases with the pump power [1, 4], the measured time delay in Fig. 5(a) shows for almost all gain bandwidths a slight decrease with increasing pump power. This behaviour indicates that the measurement is done in the saturation regime [14]. The achieved maximum fractional time delay of approximately 1.3 Bit is comparable to the measurement results for a single gain slow-light system in [5].

Figure 5(b) shows the FWHM ratio in relation to the pump power at different SBS gain bandwidths. The FWHM ratio is the reference pulse width divided by the SBS slow-light system output pulse width. If the SBS gain bandwidth exceeds the pulse bandwidth, a power can be determined where pulse broadening is totally cancelled. In comparison to the simulation results in Fig. 2, the measurement values are slightly better, but the trend is almost the same. As an explanation for the better FWHM values we assume a difference between the threshold value used in the simulation and the real value, which results in different SBS gain coefficients. The requirement for greater pump powers in the measurement can have several reasons. Firstly, the Eq. (2) and (3) follow the assumptions in [7], which proofed well for our predictions. A constant factor < 1 would reduce the impact of the SBS terms in the DES (1) and therefore increase the sufficient pump power. Another reason for the power difference can be found by the fact, that in the simulation all waves have a constant polarization. Due to the polarization dependency of the SBS and a random polarization of both waves in our experimental setup, the effectiveness of the SBS in the measurement is lower than in the simulation.

5. Conclusion

In conclusion, we have shown for the first time, to the best of our knowledge, a simple method for zero-broadening of pulses in a single gain slow-light system. Although the decrease in the pulse width comes at a cost of some distortion, a compression of the FWHM width of the pulse to approximately 90 % was shown in both simulation and measurement. Applications for such a system could be cascaded slow-light delays or the final section in any SBS based slow-light delay. Due to the working principle shown in Fig. 1, i.e. amplification of the weaker frequency components at the pulse spectrum boundaries, it could be possible to mitigate the broadening behaviour of other slow-light systems.

Finally, the measurement results are in a good agreement with the simulation. Contrary to the assumptions in [10], the origin of the pulse compression was not found in the group velocity dispersion, but in an increase of the FWHM bandwidth of the pulse. An explanation for deviations of the experiment from the simulation can be found in the lack of an ideal Gaussian shape for the input pulse and the broadened pump spectrum. However, further investigations of the pump spectrum would give the opportunity for a better match between the mathematical model and reality. But, we believe the described method has a significant potential for any slow-light system.

Acknowledgments

We gratefully acknowledge the financial support of the German Federal Ministry of Education and Research funding program Optical Technologies (contract number: 13N9355). R. Henker and A. Wiatrek gratefully acknowledge the financial support of Deutsche Telekom. Additionally the authors would like to thank J. Klinger of HfT Leipzig.

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