

Adjusting the Brillouin spectrum in optical fibers for slow and fast light applications

T. Schneider, R. Henker, K. U. Lauterbach, M. Junker

Deutsche Telekom AG, Fachhochschule Leipzig, Gustav-Freytag-Str. 43-45, D-04277 Leipzig, Germany
schneider@fh-telekom-leipzig.de

Abstract: We discuss the tailoring of the Brillouin spectrum by the superposition of different Stokes and anti-Stokes resonances. With this method it is possible to overcome the slow light bandwidth limitation and to enhance the pulse delay.

©2007 Optical Society of America

OCIS codes: (999.9999) Slow light; (290.5900) Scattering, stimulated Brillouin; (060.4370) Nonlinear optics, fibers

1. Introduction

Controlling the velocity of light pulses by light has attracted much recent interest since – beside a fundamental physical point of view – it offers the possibility to develop practical devices for telecommunications systems. Such devices include optical delay lines, optical buffers and optical equalizers, for instance. Beside other methods, especially the exploitation of the group velocity alteration in optical fibers due to the nonlinear effect of stimulated Brillouin scattering (SBS) is of special interest [1]. This has several reasons; i) optical fibers can be integrated seamlessly into existing systems and off the shelf telecom equipment can be used, ii) SBS works in the fibers entire transparency range and in all types of fibers, iii) a relatively large pulse delay requires only small pump powers. With SBS in optical fibers the group velocity can be controlled between 71000 km/s and more than the speed of light in a vacuum [2].

The first SBS slow and fast light experiments used the fibers natural Brillouin gain. For a signal wave this gain will be produced by a counter propagating pump wave with an optical frequency f_p . The frequency shift f_B between the pump and the line centre of the Brillouin gain ($f_p - f_B$) is around 11GHz and the gains linewidth Δf_B is around 30MHz in standard single mode fibers (SSMF) at a wavelength of 1550nm. A counter propagating wave with a frequency in the gain bandwidth will be amplified (Stokes amplification) and delayed. At a frequency around $f_p + f_B$ the SBS process generates a loss in the fiber (anti-Stokes absorption).

Here we will show how the bandwidth, slope and gain of the Brillouin spectrum can be adapted to the given application by a superposition of Stokes amplification lines with anti Stokes losses. We discuss experimental results for the enhancing of bandwidth and delay time by this method.

2. Concept

The complex wave number which describes the propagation of the pulse in the slow light medium in dependence on the frequency ω is [3]:

$$k(\omega) = n_0 \frac{\omega}{c} + \frac{g_0}{z} \left(\frac{\gamma}{(\omega - \omega_0) + j\gamma} \right) \quad (1)$$

where z is the length of the medium, γ is the half of the (full width at half maximum) FWHM-bandwidth, ω_0 the line center of the gain distribution, c is the speed of light in a vacuum; n_0 is the refractive index and $g_0 = g_B L_{\text{eff}} P_{1,2} / A_{\text{eff}}$ is the line center gain. With L_{eff} and A_{eff} as the effective area and length of the fiber, g_B as its Brillouin gain and $P_{1,2}$ as the input pump powers. The time delay due to SBS in the line center [$\omega - \omega_0 = 0$] is $\Delta T_{\text{SBS}} = g_0 / \gamma$. Whereas, for the over all gain it follows that $G = g_0$ (see Fig.1 a).

The maximum pulse delay in SBS delay lines is restricted by the pump depletion due to the inherent amplification process. In most experiments the storage capacity of slow light buffers was not much higher than 1 bit [4]. This results in a delay of around 30ns for a pulse with a FWHM bandwidth of 30ns. A method to decouple the gain – and therefore the amplification and depletion – from the time delay is the superposition of a Stokes amplification with an anti Stokes absorption line with a broader bandwidth. This concept is similar to electromagnetically induced transparency (EIT) [5]. In this case the complex wave number is:

$$k(\omega) = n_0 \frac{\omega}{c} + \frac{1}{z} \left(\frac{g_1 \gamma_1}{(\omega - \omega_0) + j\gamma_1} - \frac{g_2 \gamma_2}{(\omega - \omega_0) + j\gamma_2} \right) \quad (2)$$

with $g_{1,2}$ as the line center gains of the amplification and absorption lines and $\gamma_{1,2}$ as its bandwidths. The overall gain in the line center is reduced to $G = g_1 - g_2$, whereas the time delay stays nearly the same (see Fig. 1 b). For equal gains $g_1 = g_2 = g$ and $\gamma_2 = n \times \gamma_1$ it follows

$$\Delta T_{SBS} = \frac{n-1}{n} \frac{g}{\gamma_1} \quad (3)$$

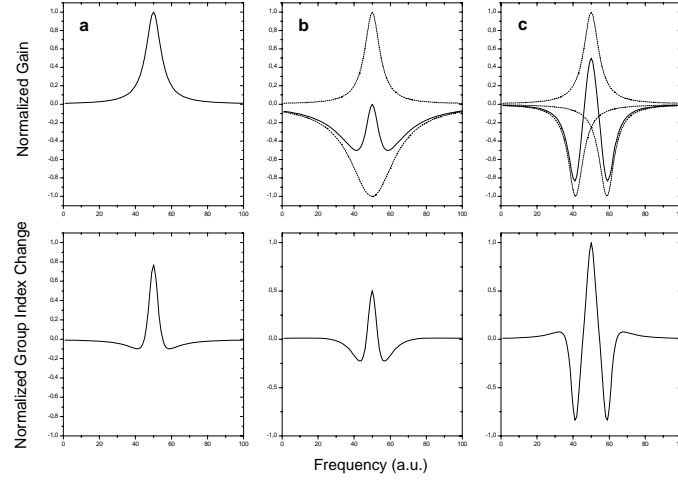


Fig. 1. Normalized Brillouin gain (top) and group index change (bottom) for three different Brillouin spectra.

With this method in just one fiber spool we achieved pulse delays of around 100ns for pulses with an initial temporal width of 34ns [6]. This corresponds to a storage capacity of nearly 3bit. The temporal width of the output pulse was around 62ns.

The method shifts the baseline of the gain and decreases its maximum but the slope of the spectrum is not altered. This can be done by the superposition of a gain with two anti Stokes absorption lines at its wings (see Fig. 1c). The complex wave number for this case can be written as:

$$k(\omega) = n_0 \frac{\omega}{c} + \frac{1}{z} \left(\frac{g_1 \gamma_1}{(\omega - \omega_0) + j\gamma_1} - \frac{g_2 \gamma_2}{\omega - (\omega_0 - \delta) + j\gamma_2} - \frac{g_2 \gamma_2}{\omega - (\omega_0 + \delta) + j\gamma_2} \right) \quad (4)$$

with 2δ as the separation between the two absorption lines. Here the amplification is decoupled from the delay process as well. For a separation of $\delta = \sqrt{3}\gamma_1$ and $\gamma_2 = \gamma_1 = \gamma$ it follows that $G = g_1 - g_2/2$ in the line center. But now, contrary to the aforementioned method, the pulse delay is not reduced but enhanced, it is:

$$\Delta T_{SBS} = \frac{1}{\gamma} \left(g_1 + \frac{1}{4} g_2 \right) \quad (5)$$

This enhancement is due to the fact that not only the baseline is shifted but the slope of the gain was changed as well. The principle set up for a pump source which can adjust the bandwidth, slope and gain of the SBS in the fiber can be seen in Fig. 2. With this source all described spectra can be produced but not all of the shown components are needed for all spectra. For producing the natural Brillouin gain of Fig. 1a only ‘‘Pump1’’ together with the Erbium doped fiber amplifier ‘‘EDFA1’’ is required, for instance.

The spectrum shown in Fig. 1b can be produced by the superposition of the gain generated by Pump1 with the loss produced by Pump2. In order to do this the frequency separation between both has to be 2 times the Brillouin shift f_B . Since the spectrum of the loss has to be broader than that of the gain the injection current of the second laser is directly modulated with a noise source (Noise2).

For the generation of the third spectrum (Fig. 1c) two loss spectra are needed. They can be produced if the noise source (Noise2) is switched off and the second Mach-Zehnder modulator (‘‘MZM2’’) is driven by a sinusoidal signal

("Sinus2") in a suppressed carrier regime. For fast light applications the inverse spectra can be produced with the shown set up.

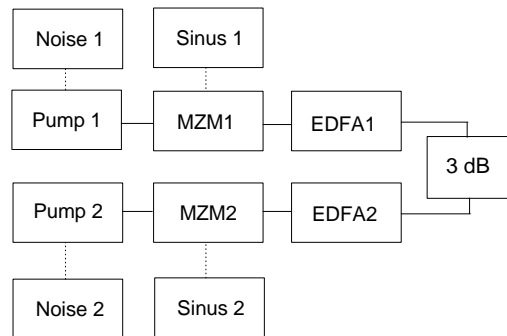


Fig. 2 Pump source for the adjustment of the Brillouin spectrum.

If the bandwidth of the gain is narrow the time delay is high but the pulses experience a strong distortion which leads to a broadening. The natural Brillouin bandwidth would result in data rates which could be delayed of only 15Mbit/s. To enhance the bandwidth the gain can be broadened by a direct modulation of "Pump1" with the noise generator "Noise1" [2]. On the other hand, to reduce distortions a flat gain profile is required. This can be achieved by a modulation of MZM1 with a sinusoidal signal in order to produce several Brillouin lines [7] another method is the modulation of MZM1 with a pulse pattern [8]. However, all these methods reduce the achievable delay times. If at the wing of a broad Stokes gain an anti-Stokes loss is introduced (with Pump2) the slow light delay arising from the wing of the anti-Stokes resonance enhances the delay at the center of the Stokes resonance [9]. If two anti Stokes resonances are introduced at both wings (as described above) the delay can be further enhanced. As can be seen from Eq. (5), the delay can be determined by the gain of the loss spectra.

Due to the fact that each pump laser produces a gain and a loss simultaneously, the enhancement of the gain bandwidth results in an enhancement of the loss bandwidth at the same time. Hence, it was widely accepted that with a SBS slow-light system the maximum attainable bandwidth is of the order $2f_B$ [10]. However, the $2f_B$ limit holds for just one pump laser source only. If the wavelength and power of a second pump laser ("Pump 2" in Fig.1) is adjusted in a manner that its Stokes resonance overcompensates the anti Stokes loss of "Pump1" the slow-light bandwidth can be drastically enhanced [11]. This concept could it made possible to open the way to data rates of 40Gbit/s and more.

3. Conclusion

In conclusion we have shown how the bandwidth, slope and gain of the Brillouin spectrum can be adapted to the slow light application by a superposition of Stokes amplification lines with anti Stokes losses. With this method it might be possible to enhance the slow light bandwidth and the delay times drastically.

References

- [1] 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).
- [2] M. G. Herraiz, K. Y. Song, L. Thevenaz, "Arbitrary-bandwidth Brillouin slow light in optical fibers," *Opt. Express* **14**, 1395-1400 (2006).
- [3] M. D. Stenner, M. A. Neifeld, Z. Zhu, A. M. C. Dawes D. Gauthier, „Distortion management in slow light pulse delay," *Opt. Express* **13**, 9995-10002, (2005).
- [4] J. B. Khurgin, "Performance limits of delay lines based on optical amplifiers," *Opt. Lett.*, **31**, 948-950 (2006).
- [5] S. Chin, M. Gonzalez-Herraiz, L. Thevenaz, „Zero-gain slow & fast light propagation in an optical fiber," *Opt. Express* **14**, 10684-10692 (2006).
- [6] T. Schneider, M. Junker, and K.U. Lauterbach, „Time delay enhancement in stimulated Brillouin scattering slow light systems," *Opt. Lett.* **32**, 220-223 (2007).
- [7] Z. Lu, Y. Dong, Q. Li, "Slow light in multi-line Brillouin gain spectrum," *Opt. Express* **15**, 1871 – 1877 (2007).
- [8] T. Tanemura, Y. Takushima, K. Kikuchi, "Narrowband optical filter, with a variable transmission spectrum, using stimulated Brillouin scattering in optical fiber," *Opt. Lett.* **27**, 1552 - 1554 (2002).
- [9] Z. Zhu, A. M. C. Dawes, D. J. Gauthier, L. Zhang, A. E. Willner, "Broadband SBS Slow Light in an Optical Fiber," *J. Lightw. Technol.* in print (2007).
- [10] Z. Zhu, A. M. C. Dawes, D. J. Gauthier, L. Zhang, and A. E. Willner, „12-GHz-Bandwidth SBS Slow Light in Optical Fibers," in *Proc. of OFC 2006*, paper PD1 (2006).
- [11] T. Schneider, M. Junker, and K. U. Lauterbach, "Potential ultrawide slow-light bandwidth enhancement," *Opt. Express* **14**, 11082-11087 (2006).