Potential ultra wide slow-light bandwidth enhancement

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Abstract: We describe a method which has the potential to enhance the bandwidth of Brillouin based slow-light delay lines drastically. It is based on the overcompensation of the anti Stokes loss spectrum by additional pump sources. With this method it might be possible to overcome the bandwidth limit of Brillouin scattering which for one pump wave is given by two times the natural Brillouin shift in the incorporated waveguide. We will show experimentally that pulses can be delayed in the overcompensated loss spectrum.

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

References and links

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1. Introduction

The control of the velocity of light pulses by light is a fascinating field of physics [1-3]. But, there are a number of possible applications for this technique as well. Such applications include buffers in a packet switched optical network, the synchronization of different bit streams and the equalization of a distorted optical data stream for instance [4]. For the speed control of light pulses several different mechanisms and material systems can be used. Among these are ultra cold [2] and hot [5] atomic gases, Rubidium vapor [6], semiconductor nanostructures [7], quantum well [8] and quantum dot [9] systems and photonic crystal waveguides [10]. For optical signal processing in the telecommunications area the exploitation of nonlinear effects in optical fibers can be used as well. This offers several advantages because fibers can be integrated seamlessly into existing optical systems. Beside other nonlinearities especially the effect of stimulated Brillouin scattering (SBS) is of special interest [11, 12]. This has several reasons; the SBS requires only small pump powers for a relatively large pulse delay, off the shelf telecom equipment can be used and SBS works in all types of fibers and in the fibers entire transparency range. With SBS in optical fibers group velocities between 71000 km/s and more than the speed of light in a vacuum were observed [13].

On the other hand, SBS has a very serious disadvantage; in standard single mode fibers the natural bandwidth of Brillouin scattering is only around 30 MHz for the telecommunications wavelength range. This results in data rates of only 15 Mbit/s that can be delayed with such a system. To overcome this limitation several techniques for the bandwidth enhancement of slow-light were proposed. Due to the fact that the spectral width of the Brillouin gain is the convolution between the natural Brillouin bandwidth and the pump spectrum the slow-light bandwidth is determined by the pump if its spectrum is much broader. In Ref. [13] the pump laser was directly modulated with a pseudo random bit sequence (PRBS) with a bit rate of 38Mbit/s. The result was a broad pump spectrum of 325MHz. In Ref. [14] the slow-light bandwidth was expanded to 1.9GHz by modulating the pump laser directly with a Gaussian noise source. The same concept was exploited in Ref. [15] to increase the SBS bandwidth to 12.6 GHz in a highly nonlinear fiber with a Brillouin shift of $f_B = 9.6$GHz.

It is widely accepted that with a SBS slow-light system the maximum attainable bandwidth is of the order $2f_B$ [15, 16]. According to this, with a SBS-based slow-light delay system data rates of 10 Gbit/s can be delayed at most. However, in optical telecommunications bit rates of 40Gbit/s and more are commonly used. Here we will show that the $2f_B$ limit holds for just one pump laser source only. With more than one independent pump laser the slow-light bandwidth can be enhanced drastically.

2. Theory

Stimulated Brillouin scattering is a nonlinear interaction between a strong pump wave and a density modulation (acoustic wave) in the fiber. A part of the pump wave power can be backscattered at the acoustic wave. This backscattered wave is called Stokes wave. Due to the fact that the pump and the acoustic wave have a relative velocity to each other, the Stokes wave is shifted in frequency by the so called Brillouin shift f_B. The beating between pump and Stokes wave can increase the density modulation and if the pump power is above a certain threshold the process is stimulated.

From a practical point of view a SBS slow-light system can be seen as a Brillouin amplifier. A strong pump wave with a frequency f_P which propagates in one direction generates a gain for a counter propagating Stokes wave at a frequency around $f_P - f_B$. For a modulated pump wave the complex Brillouin gain spectrum in the fiber is [14]

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$$g_S(f_S) = g_0 I_0 \frac{\Delta f_B / 2}{(\Delta f_B + \Delta f_P)/2 - i(f_S - [f_P - f_B])} \tag{1}$$

with Δf_B as the natural linewidth of Brillouin scattering, g_0 is the gain factor at the line center, I_0 the intensity and Δf_P the full width at half maximum wavelength of the pump field. The real part of Eq. (1) leads to an amplification of the counter propagating Stokes wave, whereas the imaginary part results in an accompanied phase shift. The strong frequency dependence of the propagation constant change of the Stokes wave leads to a change in the group velocity which in turn changes the arrival time of the pulse at the fiber output. As can be seen from Eq. (1), if the pump field is much broader than the natural Brillouin linewidth, the spectrum of the Brillouin gain in the fiber is determined by the pump field spectrum.

If at the same time a wave with a frequency shift f_P+f_B propagates in the fiber it acts like a pump wave for the counter propagating wave with the frequency f_P, i.e. optical power is scattered from this wave to the pump. Therefore, at a frequency around f_P+f_B the SBS process generates a loss in the fiber (anti Stokes absorption). This loss is translated into a higher group velocity. The gain and loss spectrum for a pump laser with a frequency f_P is shown in Fig. 1 (dashed line).

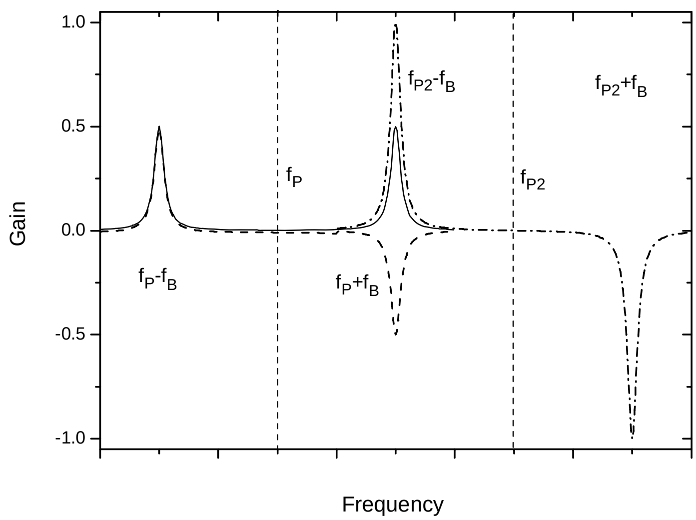

Fig. 1. Normalized SBS gain and loss spectrum (Lorentzian) for one and two overlapping pump laser sources separated by $2f_B$.

The spectral distribution of the loss follows again Eq. (1). As can be seen from Fig. 2 (top), the gain spectrum can be broadened up to two times the Brillouin shift. A further broadening leads to a compensation between gain and loss or smaller and higher group velocity. However, this limit holds for just one pump source only. If a second pump with a frequency separation which corresponds to two times the Brillouin shift ($f_{P2} = f_P + 2f_B$) is injected into the fiber, it generates a gain at a frequency $f_{P2} - f_B$. This is the spectral region of the loss spectrum generated by the first laser (dashed dotted line in Fig. 1). If the power of the second laser is higher than that of the first one the loss can be overcompensated which results in a net gain (solid line in Fig. 1).

Due to the fact that the net gain is the superposition between the individual gains a very broad slow-light bandwidth will be generated if the spectrum of each pump laser is broadened up to the Brillouin shift and higher, as can be seen from the bottom of Fig. 2. The amplification process by two independent pump sources leads to no additional phase

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alteration of the amplified wave [17]. A further enhancement of the bandwidth can be expected if more than two pump lasers are incorporated in the same manner.

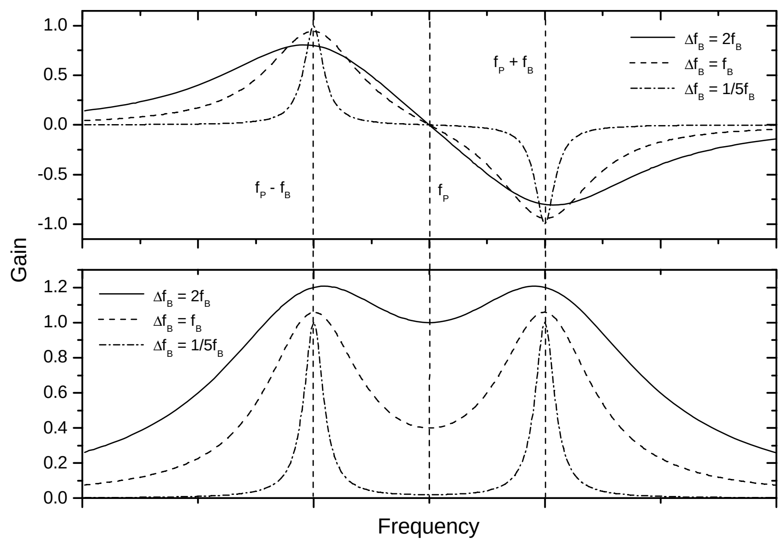

Fig. 2. Brillouin gain spectra (Lorentzian). Top: for one pump laser. Bottom: for two pump lasers.

3. Experiment

To investigate our idea we used the experimental set up shown in Fig. 3. A noise source with a bandwidth of 24MHz modulates the current of two laser diodes directly. The relation between the output powers of these pump lasers can be controlled with a tunable coupler. The following EDFA amplifies both pump waves, during this process their relative power relation remains the same. The pump waves are coupled into a 50km SSMF via a circulator. We used such a very long fiber in order to minimize the required pump powers. From the other side the very narrow wave (<1MHz) of a fiber laser was coupled into the same fiber via a Mach-Zehnder modulator. The MZM was driven by a waveform generator and the amplified or delayed signal was detected by a photodiode and interpreted by an oscilloscope.

4. Results and discussion

First we measured the bandwidth of the generated Brillouin gain in the fiber. Therefore, we drove the MZM in a suppressed carrier regime with a sinusoidal signal generated by the waveform generator. Due to the suppressed carrier amplitude modulation two sidebands will be generated in the output of the MZM. By changing the frequency we were able to scan one of the sidebands through the Brillouin gain spectrum. For this measurement we used an optical power meter instead of the photodiode and the oscilloscope in Fig. 3. The result is shown in Fig. 4.

As can be seen, the loss spectrum of LD1 is in fact overcompensated by LD2 and we have a broad positive gain on both sides of LD1. For this experiment the spectra of both laser diodes were broadened by the noise source and the output power of the EDFA was 23dBm. Owing to different direct modulation properties of the LD mounts, the SBS bandwidths and heights are different. Unfortunately our experimental equipment is not sufficient to broaden the Brillouin gain further since in the moment we neither have a broadband noise source nor a high power EDFA.

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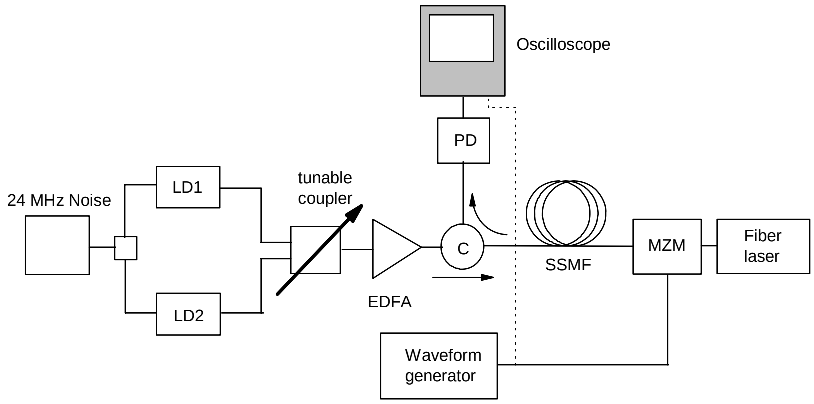

Fig. 3. Experimental set up. MZM: Mach Zehnder modulator, PD: photodiode, LD1, LD2: laserdiode, EDFA erbium doped fiber amplifier, SSMF: standard single mode fiber, C: circulator.

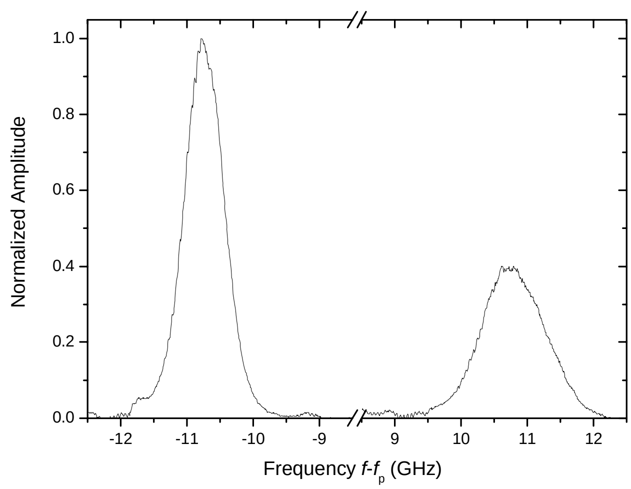

Fig. 4. SBS gain spectrum around laser 1.

To show the slow-light behavior of our approach we delayed optical pulses with the overcompensated loss spectrum at f_P+f_B. The pulses were generated by the waveform generator and had a temporal width of 40ns. For the detection of the pulse delay we used a fast photodiode together with an oscilloscope, as shown in Fig. 3.

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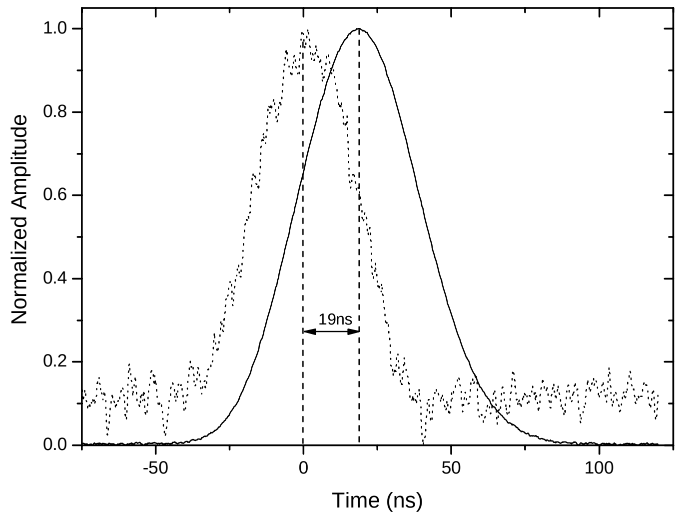

Fig. 5. In the overcompensated anti Stokes spectrum delayed pulse (solid) and reference.

The delayed pulse (solid) together with the reference is shown in Fig. 5. For a pump power of 12.7dBm at the EDFA output the pulse delay was 19ns in the overcompensated anti Stokes Brillouin spectrum. To achieve a high delay we switched the noise source off therefore, the overcompensated gain had a spectral width which corresponds to the natural Brillouin gain in the fiber only. As can be seen, the pulse was broadened due to the delay process. Since this broadening depends on the Brillouin gain bandwidths we assume that the pulse broadening can be reduced significantly if the pump laser bandwidth is enhanced. A broader bandwidth results in a lower pulse delay but this can be compensated by a higher pump power. In Ref. [18] we have shown that for the same time delay the distortion can in fact be reduced with different independent Brillouin gains.

5. Conclusion

In conclusion we have shown how the bandwidth limit of SBS based slow-light systems - which for one pump laser is of the order of two times the natural Brillouin shift - can be overcome. The method is based on the overcompensation of the anti Stokes loss spectrum by additional pump sources. In an experiment we have shown that by the incorporation of an additional pump source it is possible to produce a net gain on both sides of the pump wave spectrum. In the overcompensated loss spectrum pulses can be delayed. The concept is not limited to only two pump laser sources. The determination of the applicability and limitations of the method as well as its influence on the delay-bandwidth product require further investigations with enhanced equipment.

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