Distortion reduction in cascaded slow light delays

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A technique for the distortion reduction of delayed pulses in single and cascaded slow light delay lines is demonstrated. The method is based on the overlap of different independent Brillouin gains. With three Brillouin lines a distortion reduction of around 30% in a two-segment delay line was achieved.

Introduction: An all-optical control of velocity of light pulses can be carried out by the concept of slow and fast light. Since it offers the possibility to develop practical devices for telecommunications systems such as optical delay lines, optical buffers and optical equalisers it has attracted much recent interest. Beside other methods the exploitation of the group velocity alteration in optical fibres due to the nonlinear effect of Brillouin scattering (BS) is of special interest [1].

Contrary to other slow light techniques BS has a number of advantages: BS requires only small pump powers, off-the-shelf telecommunications equipment can be incorporated, the achievable delay can be high and the propagating fibre by itself can be used for the all-optical packet delay. In a standard singlemode fibre the maximum time delay can be as high as 60 ns but it is restricted by the gain saturation of stimulated Brillouin scattering in the fibre. This saturation defines the maximum pump power for a slow light delay line. A method to increase the achievable time delay drastically is the cascading of different fibre segments [2]. Each segment is pumped independently and due to unidirectional optical attenuators between the segments the pump wave is localised in the segment and the periodical amplification of the pulse can be compensated for. With four uniform fibre spools Song *et al.* [2] reached a time delay of 152 ns. On the other hand, owing to the narrow gain of BS the pulses experience a considerable distortion in Brillouin delay lines. In the mentioned setup described in [2] the pulses were broadened from 42 to 102 ns, for instance.

The pulse-broadening factor B is the relation between the temporal durations of the pulses at the output τ_{out} and input τ_{in} of the delay line; it is given by [1]

$$B = \frac{\tau_{out}}{\tau_{in}} = \left[1 + \frac{16 \ln 2}{\tau_{in}^2 \Gamma_B^2} G\right]^{1/2} \quad (1)$$

where $G = g_0 I_p L$ is the gain parameter with L as the length of the fibre, I_p as the pump intensity and g_0 as the Brillouin gain factor in the line centre of the gain distribution. According to (1) the pulse broadening is inversely proportional to the Brillouin gain linewidth $\Gamma_B/2\pi$. Therefore, a higher linewidth leads to a smaller broadening of the pulse. On the other hand, the maximum time delay is [1] $\Delta T_d = G/\Gamma_B$. Hence, to achieve the same time delay a medium with a broader Brillouin linewidth requires a higher gain. Together with (1) the broadening factor for a fixed time delay can be written as

$$B = \left[1 + \frac{16 \ln 2}{\tau_{in}^2 \Gamma_B} \Delta T_d\right]^{1/2} \quad (2)$$

Therefore, a time delayed pulse is always broader than it was at the input of the delay line. But its unavoidable broadening can be reduced by a higher linewidth of the Brillouin gain. This linewidth depends on environmental conditions such as temperature and stress, and on the bandwidth of the pump source [3]. By a modulation of the pump with a noise signal the slow light bandwidth can be increased to 1.9 GHz [4]. On the other hand, if the bandwidth is not uniform the modulation can lead to additional distortions of the delayed pulse.

Here we present a method for the uniform broadening of the slow light bandwidth, which leads to a reduction of the pulse distortions. The method is based on the overlap of different Brillouin lines. These Brillouin lines can be generated by a modulation of the pump source or by different pump sources. The main idea is illustrated in Fig. 1. Six independent pump lines, generated by two modulated laser sources for instance, are grouped together with a frequency separation that corresponds to the natural Brillouin linewidth in the fibre. For the simulation we assumed this linewidth as 24 MHz. Because of the overlap of the gain curves, the overall Brillouin gain shows a uniform and broad distribution; via the phase change of the wave this distribution is translated into an alteration of the group index n_g which in turn leads to a modification of the group velocity $v_g = c/n_g$, with c as the speed of light in a vacuum. As can be seen from Fig. 1, the group index distribution is uniform over the whole bandwidth, which should result in a low distortion of the delayed pulses.

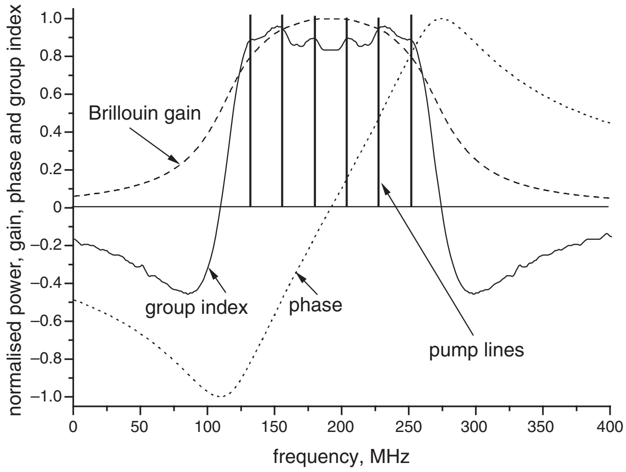

Fig. 1 *Simulated Brillouin gain, phase, and group index for six pump lines separated by natural Brillouin linewidth of 24 MHz*

Experimental setup: We tested this idea with the experimental setup shown in Fig. 2. Pulses with a wavelength of 1550 nm, a repetition rate of 700 kHz and a temporal duration of 42 ns were produced with a modulator (Mod1) driven by a generator (Gen.1). Afterwards they were delayed in a two-stage delay line, which consists of two standard singlemode fibres with a length of 50 km. We choose these very long fibres in order to reduce the required pump powers. Both fibres are pumped with the same pump source. As pump source we used a distributed feedback (DFB) laser at a wavelength of 1550 nm tunable via its temperature. The optical power was amplified with an erbium-doped fibre amplifier (EDFA) and injected into both segments. To produce three different Brillouin lines the pump was modulated with a 17.5 MHz sinusoidal signal. We adjusted the modulator so that the pump and the two modulation sidebands had the same amplitude. The delayed pulses were measured with a photodiode and an oscilloscope.

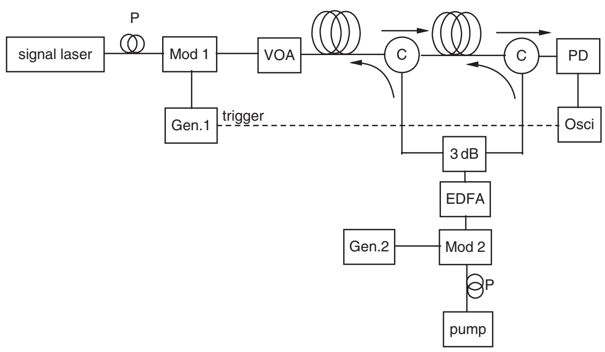

Fig. 2 *Experimental setup*

P: polariser; Gen: generator; Mod: modulator; VOA: variable optical attenuator; C: circulator; 3 dB: coupler; PD: photodiode; Osci: oscilloscope

Results: First, we measured the pulse-broadening for only one segment of Fig. 2. The broadening of the pulse against time delay is shown in Fig. 3. To achieve the same time delay the modulated pump requires a higher pump power. Nevertheless, the resulting pulse broadening is smaller, as can be seen from Fig. 3.

If two segments are used the effect is even more obvious. In Fig. 4 the output pulses of a two-segment delay line for a time delay of 33 ns are shown together with the reference. Contrary to the delayed pulses the reference propagates through the fibres without amplification. Hence, it is rather small and noisy. For the time delay shown the input pulse was adjusted with the variable optical attenuator to a power of −12 dBm in the unmodulated case. Both segments were pumped with an optical power of 6.33 dBm. The resultant output pulse had a temporal width of 59.8 nm, which is 1.42 times the width of the input signal. To achieve the same time delay for the modulated case we needed a higher gain G in the two segments. According to (1) this would result in a higher broadening of the pulse but the resultant broadening of the pulse is reduced since the Brillouin bandwidth is enhanced drastically at the same time. For a time delay of 33 ns we measured a width of 48 ns, which is only 1.14 times that of the input pulse. For the higher gain the power of the input pulse was reduced to −31.4 dBm and the pump powers were 11.5 dBm.

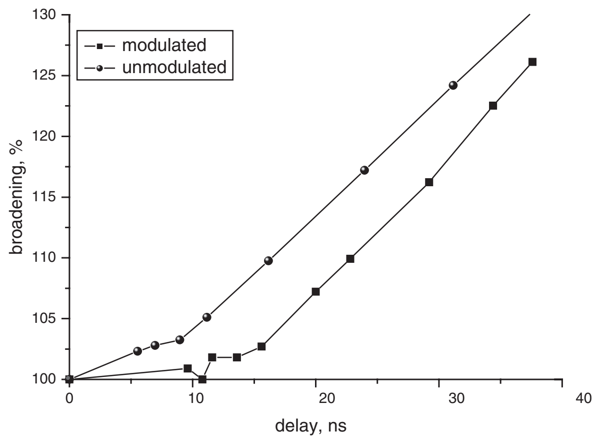

Fig. 3 *Pulse broadening against time delay for one delay segment*

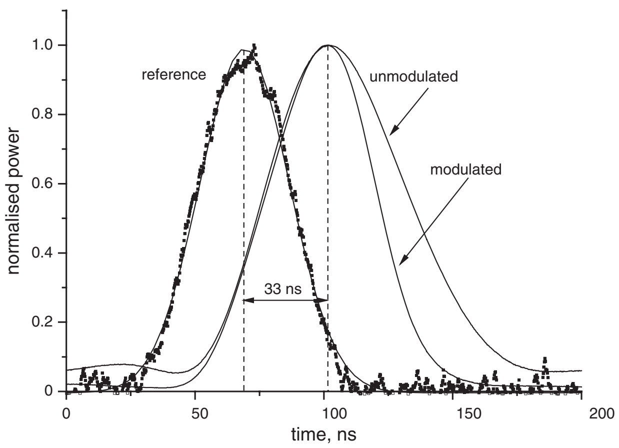

Fig. 4 *Time delayed output pulses of two-segment delay line for modulated and unmodulated pump source*

Conclusions: We have demonstrated a technique for the distortion reduction of delayed pulses in single and cascaded slow light delay lines. The method is based on the uniform bandwidth enhancement of Brillouin scattering due to the overlap of different independent Brillouin gains. In a two-segment delay line we achieved a distortion reduction of around 30% with three Brillouin gains generated by a modulation of the pump wave. Adding more Brillouin gains with additional pump sources, for instance, can further enhance this method. Beside a distortion reduction the higher Brillouin bandwidth results in a higher data rate which can be delayed with such delay lines.

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