Adapting the Slow Light spectrum in optical fibers for delay enhancement

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Abstract *A simple method for the adaptation of the slow light bandwidth of optical fibers is shown. With this method it is possible to change the bandwidth, gain and slope of Brillouin scattering in optical fibers.*

Introduction

There has been great recent interest in so called slow and fast light systems based on physical effects to reduce or accelerate the group velocity of optical pulses since they offer a great practical potential. Slow-light delays can be used in all-optical packet routers, buffers in a packet-switched optical network, for the synchronization of different bit streams and for the distortion reduction in an optical equalizer, for instance [1].

Beside other methods the exploitation of the group velocity alteration in optical fibres due to the nonlinear effect of stimulated Brillouin scattering (SBS) is of special interest [2]. Contrary to other slow-light techniques SBS has a number of advantages: off the shelf telecommunications equipment can be incorporated, SBS requires only small pump powers, the achievable delay can be high and the propagating fibre by itself can be used for the all-optical packet delay. On the other hand, the maximum achievable time delay is restricted by the depletion of the pump wave in the fibre. This saturation effect defines the maximum pump power for a slow-light delay line. In a standard single mode fibre (SSMF) the maximum time delay for a pulse with a temporal duration of around 30 ns is not much more than 30 ns [3].

A promising method to enhance the achievable time delay is the decoupling of the time delay from the Brillouin amplification [4]. This leads to very high pulse delays of around 100 ns [5] in just one fibre loop. The decoupling can be done by a superposition of a Brillouin gain with a broad loss. As a result the baseline of the Brillouin gain is shifted and the gain maximum is decreased. However, this method requires very high pump powers.

Here we will show a simple method to adapt all properties of the Brillouin spectrum like bandwidth, slope and gain to the given application. The amplification depends on the absolute hight of the Brillouin spectrum whereas, the delay is a function of its slope. Therefore, if it is possible to reduce the hight and increase the gradient of the Brillouin spectrum, very high delay times might be possible. As an example we investigated the enhancement of the time delay due to an increased slope at constant gain and pump power.

Theory

The complex wave number describes the propagation of the pulse in the slow light medium in dependence on the frequency ω. For a Lorentzain gain profile it can be written as [6]:

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

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 $g_0 = g_B L_{eff} P_{1,2}/A_{eff}$ 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 [ω - ω_0 = 0] is $\Delta T_{SBS} = g_0/\gamma$. Whereas, for the over all gain it follows that $G = g_0$. This gain is responsible for the attenuation of the pulses.

If a Stokes amplification line is superimposed with an anti Stokes absorption with a broader bandwidth, amplification and delay are decoupled from each other. This concept is similar to electromagnetically induced transparency (EIT) [4]. In this case the complex wave number can be written as:

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

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 is $\Delta T_{SBS} = (n-1)/n \times g/\gamma$, for equal gains $g_1 = g_2 = g$ and $\gamma_2 = n \times \gamma_1$. Therefore, the maximum time delay depends on the broadening factor of the loss spectrum.

If a Lorentzian gain is superimposed with two anti Stokes absorption lines at its wings the complex wave number is:

$$k(\omega) = n_0 \frac{\omega}{c} + \qquad (3)$$

$$\frac{1}{z}\left(\frac{g_1\gamma_1}{(\omega-\omega_0)+j\gamma_1} - \frac{g_2\gamma_2}{\omega-(\omega_0-\delta)+j\gamma_2} - \frac{g_2\gamma_2}{\omega-(\omega_0+\delta)+j\gamma_2}\right)$$

with 2δ as the frequency separation between the two absorption lines. 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.

So, again the amplification is decoupled from the delay. Now, contrary to the aforementioned method, the pulse delay is not reduced but enhanced by the loss spectra, it is:

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

This enhancement is due to the fact that the slope of the gain was changed.

Experiment

Figure 1 shows the principal experimental set up.

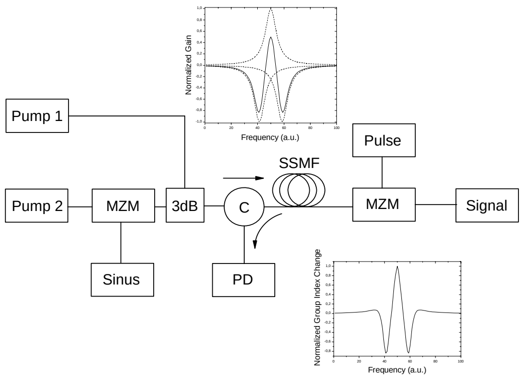

Fig. 1. Principal experimental set up (C; Circulator, SSMF; standard single mode fiber, PD; photodiode, MZM; Mach-Zehnder modulator).

The Lorentzian gain produced by Pump 1 is superimposed with two loss spectra which are produced by Pump 2 together with a Mach-Zehnder modulator (MZM). In order to do this the optical frequency of the wave produced by Pump 2 is two times the Brillouin shift (around 22 GHz) lower than the optical frequency of Pump 1. This wave is modulated with a sinusoidal signal by the MZM. Due to the fact that the MZM is driven in a suppressed carrier regime only two sidebands are present behind the MZM. In the 50 km long SSMF these sidebands produce two loss spectra which are superimposed with the gain generated by Pump 1. The resultant Brillouin spectrum can be seen in the upper inset and the corresponding group index change is shown in the lower inset of Fig. 1. Both pump lasers are distributed feedback (DFB) laser diodes.

The optical pulses are produced by a pulse generator which drives another MZM. The optical carrier signal for the pulses is generated by a fiber laser (Signal). The wavelengths of the signal and pump lasers were around 1550 nm. The delayed pulses were coupled out with the circulator (C) and interpreted with a photodiode (PD) and an oscilloscope. The results are shown in Fig. 2.

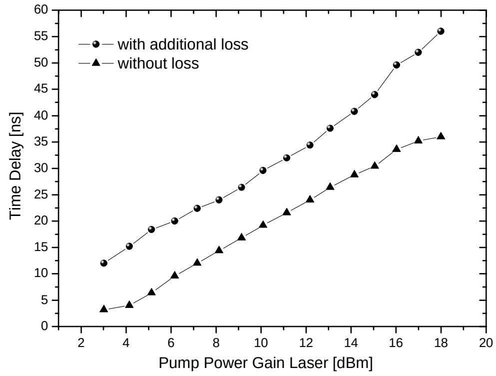

Fig. 2. Time delay as a function of the pump power of the gain laser.

As can be expected from the theory, the time delay increases with a higher power of the gain laser (Pump 1 in Fig. 1). If no additional loss spectra are present the time delay has a maximum of around 35 ns. If the pump power is increased further the pulse delay is saturated. With the two loss spectra ($\delta = \sqrt{3}\gamma_1$, P_{in} = 14.8 dBm), the gradient of the Brillouin spectrum is increased. This leads to a higher group index change and therefore, to a higher time delay for the same pump power of the gain laser. Due to the fact that the absolute gain is reduced as well with this technique, for high pump powers the time delay is not saturated.

Conclusions

We have shown a simple method to adapt the SBS bandwidths of optical fibers to the given application. As an example we have presented the enhancement of the time delay of SBS based slow light systems due to an increased gradient of the Brillouin spectrum. But, the method can be used to other applications like filtering or separate amplification as well.

References

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