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(Article begins on next page)

Zero-Gain Slow Light in Optical Fibres

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Abstract *Generation of optical delays with minor amplitude change are realized through the superposition of gain and loss profiles generated by stimulated Brillouin scattering. It results in synthesized spectral profiles identical to an ideal electromagnetically-induced transparency.*

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Introduction

Slow light is known to be a very attractive approach to achieve all-optical delay lines and to provide a timing tool for photonics signal processing. A significant step towards real applications has been achieved last year when slow light was experimentally and efficiently demonstrated in optical fibres using stimulated Brillouin scattering [1] and later other nonlinear interactions [2,3] with larger natural bandwidth but much reduced efficiency.

Actually stimulated Brillouin scattering (SBS) has proved to an unprecedented and unmatched flexible tool for the generation of slow light regarding its spectral tailoring capability. Indeed, a large variety of gain spectral profile can be obtained by properly modulating the pump spectrum. For instance fast light in gain regime was achieved using a two-tone pump spectrum, resulting in overlapping gain profiles and eventually a reversed linear phase variation [4]. More recently it was demonstrated that the bandwidth of SBS-based slow light can be made arbitrarily large by actively broadening the pump spectrum using random direct current modulation of the pump laser [5], to ultimately reach a 10 GHz bandwidth [6].

All these techniques suffer from the drawback of a significant amplitude change associated with the delaying effect. This may be highly impairing in a real system. Indeed, the delaying effect in slow & fast light is intimately related to a narrowband gain or loss process. For instance a one-pulse width delaying gives rise to a large 30dB pulse amplitude change using SBS.

We demonstrate here that the high flexibility of SBS offers the possibility to synthesize a gain spectral profile, so that a signal delay or advance is achieved with an ideally absolute null amplitude change. This can be obtained by the combination of gain and loss spectral profiles with identical depth but different width, resulting in a net zero gain and a differential delaying effect.

Principle

Slow & fast light is observed when a sharp spectral change in the medium's transmission results in a steep linear variation of the effective refractive index with wavelength. This in turn results in a strong group velocity change at the exact centre of the resonance.

For a gain/loss process following a Lorentzian spectral distribution such as SBS, a signal propagating in a medium showing a linear gain G will experience a net amplitude change by a factor exp(G) together with a delay $T=G/(2\pi\Delta\nu)$ where $\Delta\nu$ is the half width at half maximum of the Lorentzian distribution.

The delay T thus depends on 2 parameters: the linear gain G (negative for loss) *and* the bandwidth $\Delta\nu$ of the gain/loss process. It is well known that a gain can be generated using SBS by placing the pump frequency at a frequency $+\nu_B$ above the signal frequency, ν_B being the Brillouin shift. But an equivalent loss can be generated as well simply by placing the pump frequency at a frequency $-\nu_B$ below the signal frequency. In this latter case the linear gain is negative and pulse advancement is observed [1].

Now let superpose in the frequency domain a SBS gain with linear gain $+G_1$ and a bandwidth $\Delta\nu_1$ together with a SBS loss with linear negative gain (thus loss) $-G_2$ and a bandwidth $\Delta\nu_2$. The resulting linear gain is therefore $G=G_1-G_2$ and the overall delay $T=G_1/(2\pi\Delta\nu_1)-G_2/(2\pi\Delta\nu_2)$. If $G_1=G_2$, then:

$$G = 0 \quad \textit{and} \quad T = G_{1,2}/2\pi\times(\Delta\nu_1^{-1} - \Delta\nu_2^{-1}).$$

If the bandwidths of the gain and loss spectra are substantially different, e.g. $\Delta\nu_2>>\Delta\nu_1$, it is possible to obtain a significant delay T with nevertheless a zero linear gain G. The effect is fully comparable to electromagnetically-induced transparency (EIT), in which a transparency window is opened in the middle of an absorption line.

Experimental configuration

The experimental scheme used to demonstrate the zero-gain delays is shown in Fig.1. Pump 1 is non-modulated and placed at a frequency $+\nu_B$ above signal. It thus generates a narrowband gain and the gain bandwidth is given by the natural Brillouin bandwidth of about 25 MHz. To keep a constant frequency difference between pump 1 and the signal, these 2 optical waves were generated from the same laser source using modulation and filtering [1,4] resulting in a total absence of spectral drift and a perfect centring of the signal in the gain spectrum.

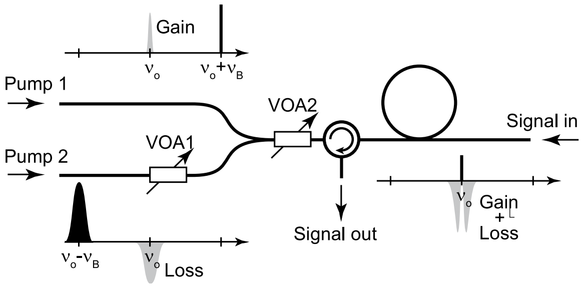

Fig.1: Experimental configuration to realize zero-gain slow light using SBS, by spectrally superposing gain and loss spectra from different sources showing different linewidths. VOA: variable optical attenuator.

Pump 2 is generated from a distinct laser diode with a spectrum substantially broadened to 238 MHz by a noise generator [5,6]. It is spectrally placed at a frequency -ν_B below the signal frequency and thus generates a broadband loss at the signal frequency. Since this loss spectrum is broad the frequency setting of pump 2 is less critical and just requires a fine tuning and a good stabilization of the laser current. The power of pump 2 must be larger than pump 1 by a factor identical to the broadening factor $\Delta\nu_2/\Delta\nu_1$ [5].

The variable optical attenuator VOA1 is used to adjust the power of pump 2, so that $G_2=G_1$. Fig. 2 shows the obtain gain/loss spectral profile, very similar to an ideal EIT profile, demonstrating that a good compensation of gain and loss can be obtained.

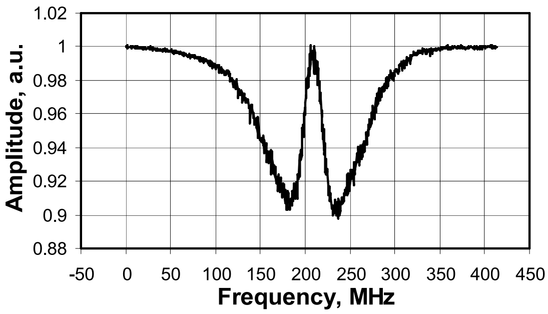

Fig.2: Amplitude of a probe signal as a function of frequency after propagation in a 2 km fibre in which a superposed SBS gain/loss profile is generated. At the centre gain and loss fully compensate.

The variable optical attenuator VOA2 is then used to vary simultaneously and identically the power of the 2 pumps, so that the gain/loss compensation is maintained at any pumping level and a zero-gain varying delay is obtained.

Results

Delay and amplitude for a 1 MHz sine modulated signal were recorded for different pump levels and are shown in Fig. 3 in linear scales. Delays comparable with the standard method [1] are obtained in a 2 km fibre, together with a maximum amplitude change of ±1.5 dB. An equivalent delay using the non-compensated standard technique would result in a 23 dB amplitude change.

These first results show that the ideal zero-gain situation is not exactly achieved, explaining the amplitude growth for low pump power. The amplitude is then decreasing for higher power certainly as a consequence of pump depletion. We are confident to obtain even flatter amplitude response in the near future.

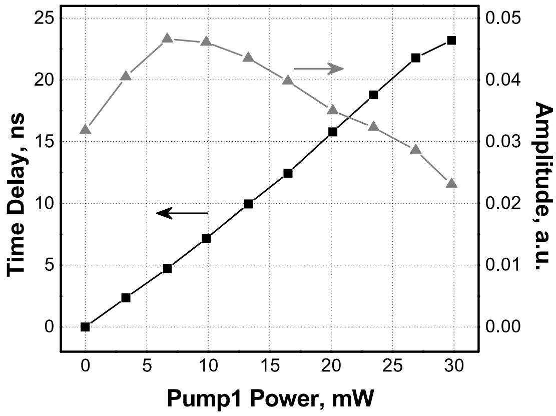

Fig.3: Delay and amplitude for a 1 MHz sinusoidal signal as a function of pump 1 power. The power of pump 2 is approx. 10 times higher than pump 1.

Conclusions

The high flexibility of stimulated Brillouin scattering to produce slow & fast light makes possible the generation of variable delays with no amplitude change. We experimentally demonstrate it in this paper using a simple configuration. We can achieve a situation identical to ideal EIT, that is up to full transparency.

In addition the same scheme can be used to generate zero-loss fast light and signal advancement, by simply swapping the spectral positioning of pump 1 and 2.

It must be pointed out that the broadband gain compensation can be produced by other type of interactions, in particular Raman, but also using doped fibres and parametric amplification.

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