New Approaches to Extending the Performance of Brillouin Based Slow Light Systems

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Abstract **We review the development of several new approaches for extending the performance of Brillouin based slow light systems. In particular we describe the use of cavity effects to enhance the achievable delays, gain saturation to decouple the delay and associated signal gain, and the use of tailored pump beams to effect reshaping and retiming of periodic signals.**

I. INTRODUCTION

Brillouin-assisted slow light has received much attention since its first demonstrations in 2005 [1, 2]. As well as being of inherent physical interest, these early experiments, carried out in a conventional fiber at room temperature, seemed to point to a possible route to the development of several important all-optical devices ranging from simple all optical tuneable delay lines through to optical buffers.

Much of the subsequent research effort has targeted, in one way or another, the pursuit of these important applications. As a consequence many of the factors limiting the technique have already been overcome. For example, ways to enhance the bandwidth of the delayed signals by broadening the Brillouin gain profile [3, 4] have been developed, and the use of extreme nonlinearity non-silica fibers has been shown to provide a way to reduce the pump power and inherent device latency, as well as to increase the effective reduction in speed [5, 6]. However, we and others, have also sought to gain a fuller understanding of the Brillouin delay mechanism, and to investigate ways of better exploiting it within more complex optical systems to enhance the gain-delay characteristics and functionality of slow light systems.

In this paper we review our work on the use of cavity effects to enhance the achievable delays, gain saturation to decouple the delay and associated signal gain, and the use of tailored pump beams to effect reshaping and retiming of periodic signals.

II. CAVITY EFFECTS

Taking into account that the dynamics of Brillouin scattering are strongly modified in the presence of external feedback [7], we investigated ways to employ an external cavity to enhance slow-light generation. The idea is that if the Brillouin peak coincides with one of the transmission maxima of the cavity, then constructive interference will take place leading to a sharpening of the gain peak. This process simultaneously narrows and enhances the gain peak, which ultimately gives rise to a reinforcement of the slow light effect that can provide delays even 100% higher than without the cavity [8]. We demonstrated this point in a slow-light system comprising a 2-m long bismuth oxide highly nonlinear fiber. The high core index creates a Fresnel reflectivity at the uncoated end facets of ~2.5% when coupled to a SMF fiber. This gives rise to a low-finesse Fabry-Perot cavity enclosing the highly nonlinear fiber. We measured a maximum delay of ~70ns for 200ns Gaussian pulses using just ~500mW pump power, as shown in Fig.1. Without the presence of the cavity our simulations predict a delay of ~30ns.

On the other hand, if the gain peak sits at one of the transmission minima the gain peak is broadened, which ultimately results in a smaller delay for the same pump power. This way the detuning of the gain peak relative to the transmission maxima of the cavity offers an additional means of control for the delay without changing the pump power.

It should be noted that although demonstrated in the context of Brillouin-assisted slow light, this cavity enhancement effect should work with any other gain-assisted slow light technique.Ultimately the slow-light enhancement takes place due to a tighter fitting of the gain bandwidth to the signal bandwidth. Therefore, this effect can be most useful whenever there is some spare gain bandwidth (e.g. when using Raman scattering).

One requirement of the technique is the existence of intrapulse interference, which limits the maximum length of the cavity. Other cavity configurations, like a ring cavity, offer better performance for shorter lengths. However, even for this higher performance configuration, the cavity length required for high speed signals would be too short to use optical fibers, and other slow light media might be required (e.g. semiconductor devices).

II. USE OF GAIN SATURATION

One of the characteristics of gain-assisted slow light systems is that once the slow light medium has been chosen, there is a coupling between gain and delay, i.e. certain gain always provides a certain amount of delay. However, this can pose problems in real systems since signals with different delays would have considerably different amplitudes. Therefore, it would be desirable to decouple these two magnitudes. We have proposed a way to achieve this by working in the pump depletion regime and by using a variable optical attenuator (VOA). Since all the delay
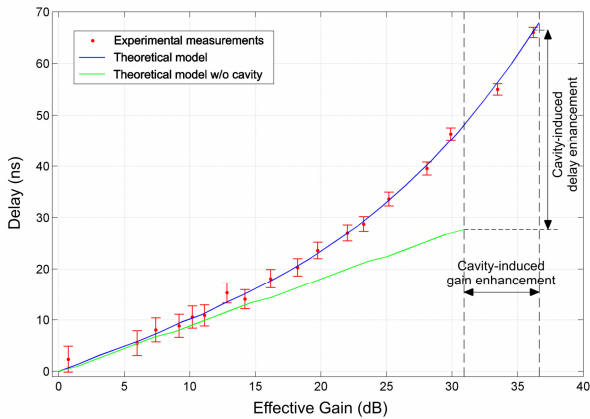
Fig.1. Experimental demonstration of slow light enhancement due to the presence of reflections. For comparison the theoretical prediction of the achievable delay without a cavity is also presented.
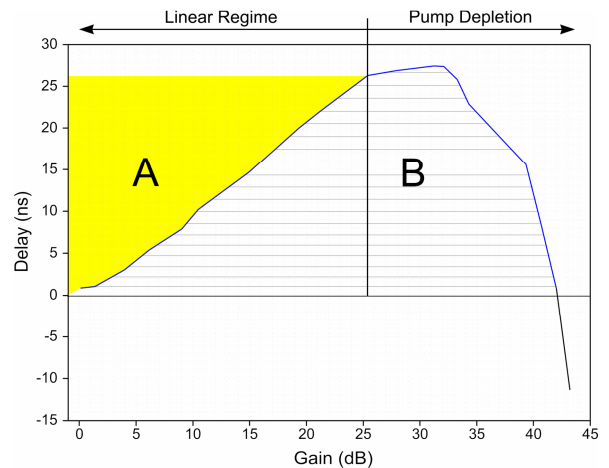

Fig.2. Delay vs. gain in a Brillouin-assisted slow-light system. The linear and pump depletion operation regimes are distinguished. Shaded area A illustrates the delay/gain combinations accessible by using an optical attenuator and operating in the linear regime. Operation in the pump depletion regime grants access to shaded areas A+B.

range offered by the fiber is swept in the pump depletion regime, the attenuation of the delayed probe under this operating condition provides access to shaded areas A+B in Fig.2 (i.e. any combination of delay/gain offered by the system), whereas only the shaded area A would be accessible if operating in the linear regime. Alternatively, the operation in the pump depletion regime can be useful to obtain more *equalized* delayed signals or even signal with different gain levels but very similar delays (around the peak of Fig.2).

As can be seen in Fig.2, the pump depletion regime is characterized by a rapid decrease in the delay with increasing gain. The decrease of induced delay is due to pulse reshaping instead of any phase phenomenon. In spite of this, we have seen in our experiments that the amount of pulse distortion induced is very little provided the probe pulses are smooth and the delay is always kept >0ns [9].

III. Use of Complex Pump Fields

Several works have attempted to broaden the narrow bandwidth of Brillouin gain, in order to make the effect applicable to telecoms signals. For example, in [3, 4] the pump was modulated by a pseudorandom bit sequence (PRBS) to uniformly broaden its bandwidth. By contrast to the continuous spectrum of a PRBS signal, a complex periodic pulse pattern exhibits a multiline spectrum that can be employed to generate a Brillouin gain comb. When appropriately handled, this process can be used to manipulate the individual harmonics of a high-speed periodic signal. This constitutes a very flexible and powerful way of signal processing that can be used for signal reshaping and/or retiming with very little gain change. It is important to remark that this technique is essentially independent of the frequency of the periodic signal.

IV. Conclusions

We have shown that gain-assisted slow light, and particularly Brillouin-assisted slow light, can be strongly influenced by elements outside the Brillouin medium. These dependencies and the modification in behavior that they

allow can be exploited in many different ways. We have presented some examples of how Brillouin-assisted systems can be engineered to enhance their functionality, such as the enhancement of the delay by using Brillouin-effects in a cavity, the decoupling of delay and gain, or the reshaping of signals by individual control of the their harmonics.

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