# Slow Light in Optical Fibers: State-of-the-Art and Perspectives 10 Years After the First Demonstration

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***Abstract*—The possibility to directly realize all-optical delay lines in optical fibers has triggered efforts of research during the past decade, with few practical outcomes. The reason is fundamental, caused by the unescapable relation between delay and distortion.**

***Keywords*—slow light, nonlinear fiber optics, optical delay line, stimulated Brillouin scattering**

## I. HISTORICAL CONTEXT

The first demonstration of the active delaying of a light pulse by massively reducing the group velocity through a nonlinear interaction was realized in 1999 in a very special medium, namely an ultra-cold atomic gas [1]. At that moment the possibility to generate slow light at room temperature - moreover in optical fibers - was simply utopic and considered like the quest of the Holy Grail. But a few years later, in 2003, a team from the University of Rochester demonstrated slow light at room temperature in a crystalline solid [2] and in 2004 our team at EPFL could make the first demonstration in optical fibers, at room temperature and at any wavelength using stimulated Brillouin scattering [3]. An independent research carried out at Cornell University obtained a similar demonstration using a different setup, published in parallel a few months later [4].

These achievements generated a huge hope and it was clearly forecast that slow light will be the preferred way to realize all-optical routers for the next generation of telecommunication networks. As usual the pioneering teams have got more skeptic comments than credits, pointing out the relatively short delays that were obtained (~30 ns) and the limited bandwidth of the system (~30 MHz). But in a matter of one year extended delays up to 160 ns were demonstrated [5] and fiber slow light systems of arbitrary bandwidth were readily implemented [6,7].

However, active experts in this field turned out to be rapidly convinced that the amount of delay obtained using slow light would never meet the requirement for all-optical buffering in telecommunications. The reason is visible in Fig. 1 where the generation of very long delays is shown, evidencing a severe distortion that occurs as a pulse broadening similar to the effect of chromatic dispersion.

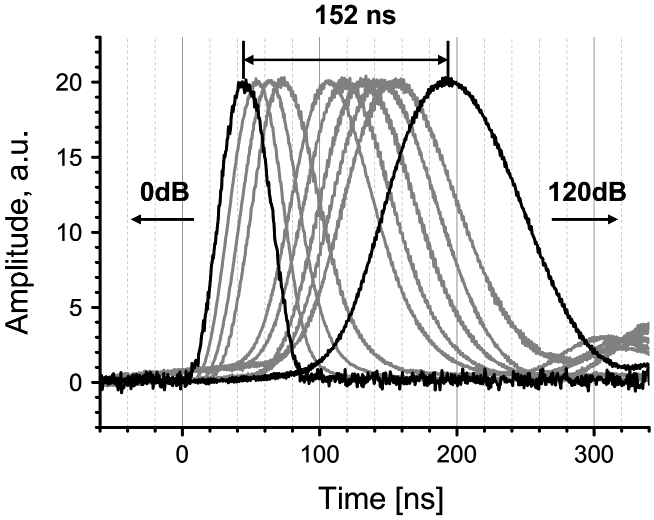

Fig. 1. Extended delays obtained by a linear slow light system based on stimulated Brillouin scattering in standard silica fibers [5], illustrating the important pulse broadening generated by such systems. The values in dB represent the overall gain of the Brillouin amplification.

Actually it is possible to delay a pulse up to its width with a tolerable distortion. In other words, if the delay is normalized to the pulse width, this fractional delay cannot exceed the unity without impairment on the signal. It can also be formulated that the product “delay × signal bandwidth” is limited to one.

It was erroneously proposed to compensate this pulse broadening by propagating in a medium showing an opposite chromatic dispersion, but the nature of the broadening in a slow light system originates from 2 distinct effects that can be in no way identified to group velocity dispersion (GVD), making illusive any attempt to compensate them with GVD.

## II. DISTORTION IN A LINEAR SLOW LIGHT SYSTEM

In the discussion hereafter it will be considered that the slow light generation can be described as a *linear time-invariant system*. This is an excellent approximation if the signal does not deplete the amplification process and there is thus no gain saturation. This is also the preferred solution for practical applications, since the response does not depend on the signal amplitude and the history in the data sequence. It should be noted that the system response can perfectly be linear even if the process generating the gain is a nonlinear optical effect. Under these conditions the system can be described by a transfer function $F(\omega)$ which solely depends on the optical frequency and not on any other signal characteristics (amplitude, …).

Exploiting the natural Brillouin gain in optical fibres, pumped by a CW single frequency laser, the transfer function shows a Lorentzian spectral profile in amplitude, as depicted in Fig. 2 with the associated phase response.

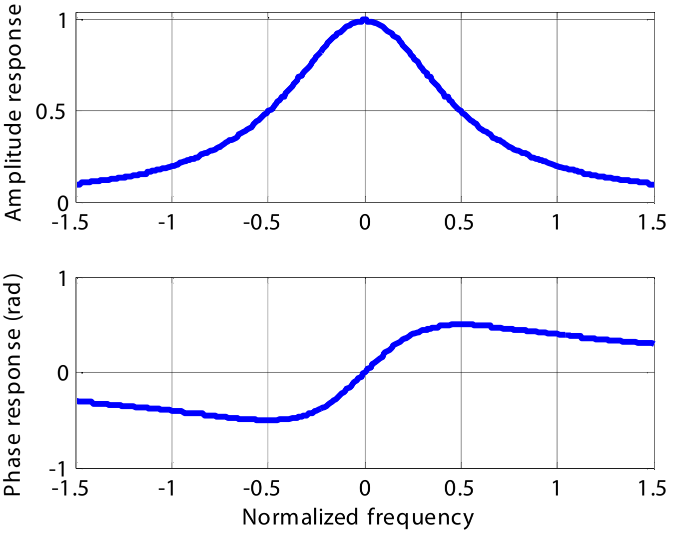

Fig. 2. Amplitude (top) and phase (bottom) response of the natural Brillouin amplification as a function of optical frequency, following a Lorentzian spectral distribution.

Over a short amplification segment the amplitude response corresponds to the real part of the transfer function, while the phase response can be identified to the imaginary part. Since the system is linear and causal, real and imaginary parts of the transfer function are correlated quantities related by Hilbert transforms. In short, if only the amplitude response is known, the imaginary part can be exactly calculated from the real part and the phase response is obtained, and vice-versa.

From Fig. 2 it can be easily deduced from the amplitude response that all frequencies in the signal won't be transmitted with equal amplitudes and a low pass filtering will occur. This is the first source of broadening designated as *amplitude distortion*. Since the amplitude response corresponds to the real part of the transfer function, this distortion cannot be compensated by GVD that is a pure phase effect that will solely be a pure imaginary contribution to the transfer function. A pure imaginary number can never nullify a pure real number.

It can also be seen in Fig. 2 that the phase response is essentially linear for close-to-zero frequencies. A perfect linearity corresponds to a pure delaying effect, which is the dominant behavior for the central signal frequencies. For outer signal frequencies higher order terms turn important, giving rise to *phase distortion*. Since the phase response is spectrally antisymmetric, only odd power terms are present in the Taylor expansion and the dominant cause of distortion will be the 3rd power term, corresponding to 3rd order chromatic dispersion. Since GVD is described by a 2nd order term, it can never compensate at all frequencies the 3rd order dispersion generated by the slow light system.

To realize a distortion-free slow light system it will be therefore required to generate an amplification profile that shows a *flat amplitude response* over the bandwidth of the signal, and simultaneously a *pure linear phase response* over the same bandwidth. It turns out to be simply impossible to generate such a combined response, as will be shown hereafter.

It must be pointed out that it is perfectly possible to synthesize any amplification spectral profile in a Brillouin fibre amplifier, by simply shaping the pump spectrum [6,8,9].

Fig. 3 shows that a flat amplitude response over a bounded spectrum gives irremediably a nonlinear phase response. Such a system shows no amplitude distortion, but is still subject to phase distortion.

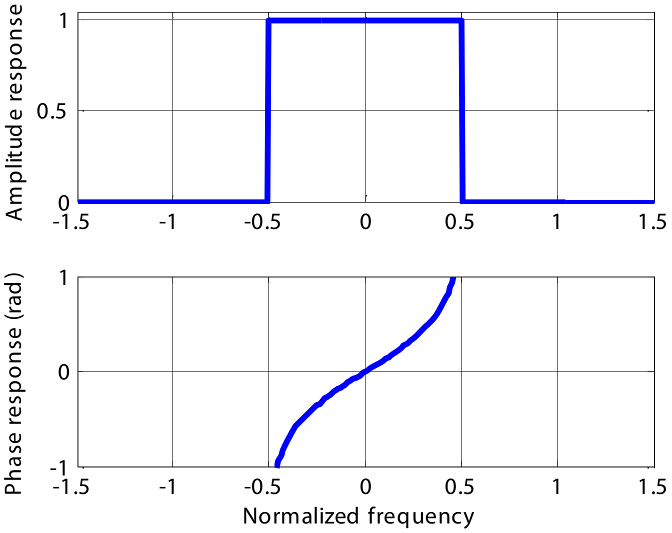

Fig. 3. Amplitude (top) and phase (bottom) response of a flat amplification as a function of optical frequency, following a rectangular amplitude spectrum.

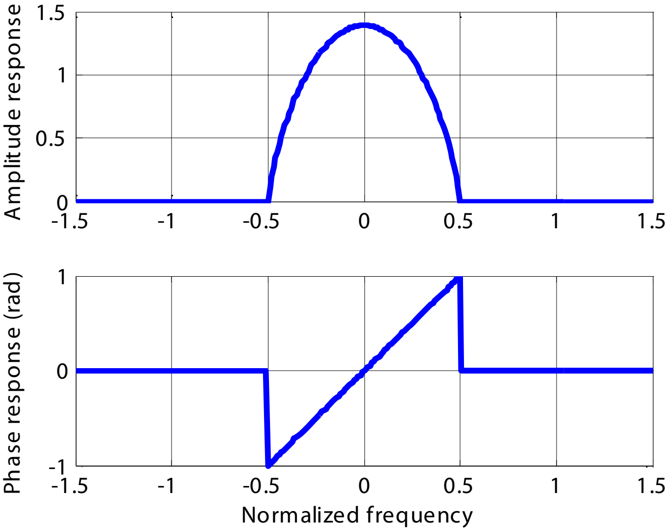

Fig. 4. Amplitude (top) and phase (bottom) response of a pure delaying system as a function of optical frequency, corresponding to a perfect linear phase response.

It is also possible to generate a gain spectrum giving a perfect linear phase response over a bounded spectrum, as shown in Fig. 4. Such a system is free of 3rd order dispersion and phase distortion, accordingly. But the amplitude response is no longer flat and a low pass filtering will result, giving rise to amplitude distortion.

It is easy to conclude from these 2 distinct attempts that ideal responses can be realized either in amplitude or in phase, but not simultaneously, so that the distortion-free linear slow light system does not exist and distortion and delaying are intimately related. This has been fully validated experimentally [10], showing a perfect match with this theoretical description. The same work has identified a gain spectral profile that minimizes distortion, but does not fully suppress it.

## III. CONCLUSIONS AND PERSPECTIVES

It has been shown that, for fundamental reasons related to the properties of causal linear systems, it is impossible to conceive a linear slow light system that does not generate distortion on the delayed signal. This hopelessly limits the product “delay × signal bandwidth” to a value close to unity. Practically, in a digital transmission, it is concretely impossible to delay a bit sequence by more than one bit duration, which is far from the requirement for optical buffering and routing. The only identified application is the resynchronization of a bit within its temporal bin.

Actually alternative techniques have been proposed to implement optically-controlled photonic delay lines which turn out to achieve a product “delay × signal bandwidth” of more than 1000 showing tolerable distortion [11].

Possibly the most impressive application of fiber optics slow light systems have been in the field of microwave photonics, where tunable filters have been demonstrated with unmatched performance [12,13].

*Acknowledgements*: the author is extremely grateful and wants to warmly acknowledge all colleagues and collaborators who contributed to the knowledge and to build this vision: Miguel Gonzalez Herrraez, Kwang-Yong Song, Sanghoon Chin, Marco Santagiustina, Jacob Khurgin, Daniel Gauthier, Nikolay Primerov, Avi Zadok, Moshe Tur, Liang Zhang, Marcelo Soto and all partners in the GOSPEL EU FP7 project. Many thanks to the Swiss National Science Foundation for supporting this research through several projects.

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