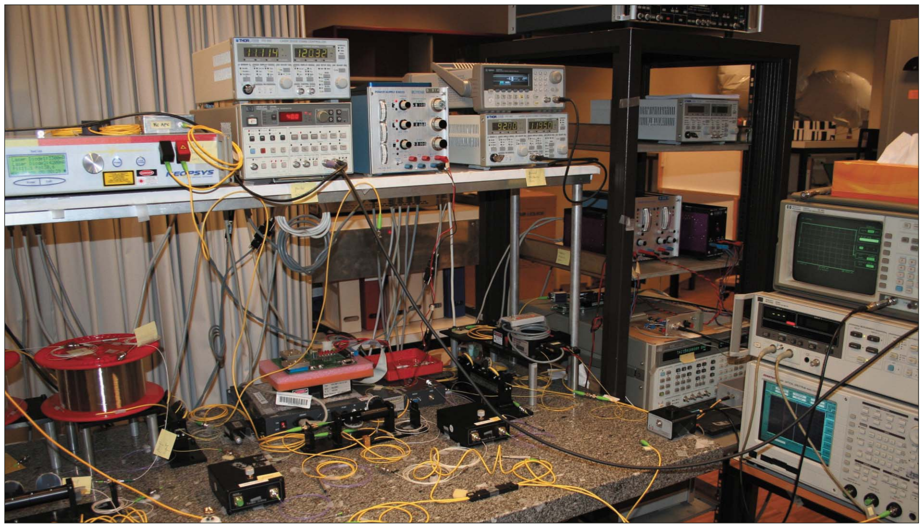
Slowing light in optical fibres sees fast progress

Slowing down light to produce optical delay lines for communication networks has advanced enormously in the last year. **Luc Thévenaz** and **Miguel Gonzalez-Herraez** chart this recent progress and describe the new challenges facing developers of practical devices.



There are still challenges to overcome before the lab-based set-ups can be turned into practical devices.

The ability to temporarily store a signal and recall it at an exact point in time is an essential function of any type of signal processing system. The development of all-optical signal processing has been seriously impaired due to the lack of timing tools. But as we advance towards all-optical systems, this situation must improve if we are to avoid bottlenecks in data transmission and routing.

The main motivation behind this line of research is the development of all-optical delay lines, buffers and routers as well as all-optical memory chips. Such devices could have important consequences for optical telecommunication and computer networks. If the complex functions of timing and routing could be performed all-optically, this would drastically boost performance and bridge the first gap towards all-optical logic functions and computation.

The active control of the speed of a light signal to generate tuneable delays offers numerous benefits and has attracted much attention. Research teams globally are striving to develop fast-access memories and optically controlled delay lines compatible with optical computing and fibre-optic communication systems.

There have been many reports of successful ways to control the group velocity of light ranging from slowing light to a near stop right through to producing a group velocity exceeding the vacuum velocity of light.

All of these fundamental experiments were based on the concept of "slow and fast light", which relies on a specific property observed in all narrow spectral resonances. Here, 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.

This effect turns out to be the strongest for the narrowest spectral resonances. For this fundamental reason, early experiments were all carried out in exotic media such as ultra-cold atomic gases or atomic transitions in crystalline solids working at well-defined wavelengths.

Until last year, there was no known method for realizing optically controlled delays in optical fibres. The major difficulty was generating narrow spectral resonances in a highly disordered material such as glass.

Things changed in January 2005 when our team at Ecole Polytechnique Fédérale de Lausanne in Switzerland discovered that an efficient nonlinear effect seen in silica, called stimulated Brillouin scattering (SBS), can generate the narrow resonances needed to produce large, observable delays (*Optics Express* **13** 82). In the same paper, we experimentally achieved a tuneable delay of 30 ns on a 100 ns optical pulse.

Encouragingly, these results were quickly independently replicated by others following the same approach. Throughout 2005, several groups demonstrated different schemes for performing all-optical delaying in optical fibres using Raman-assisted parametric amplification, wavelength conversion associated to a dispersive propagation and Raman amplification. All of these techniques tried to improve the delaying performance, in terms of bandwidth and maximum normalized delay (delay divided by the pulse temporal width). A similar approach was taken to implement compact temporary optical storage on integrated optical chips.

Stimulated Brillouin scattering

SBS can substantially modify the velocity of an optical pulse. The phenomenon itself results from the interaction between two optical waves and an acoustic wave in a medium. The effect is very efficient in optical fibres and can be observed using moderate powers in the mW range. As the name suggests, the effect can also be stimulated so that the scattered optical wave sustains and feeds the scattering acoustic wave.

SBS is traditionally observed in optical fibres by propagating an intense coherent wave called a "pump" in one direction and by observing the amplitude growth of a weak coherent "probe" wave propagating in the opposite direction along the optical fibre.

If the pump and probe waves have a small but finite frequency difference, their superposition produces a longitudinal fringe pattern that moves along the fibre at a velocity related to the frequency difference, wavelength and the refractive index of the fibre medium. ▷

This moving periodic intensity pattern gives rise to a compression wave as a result of electrostriction. For an exact frequency difference, the velocity of the pattern matches the acoustic speed in the medium and the compression wave turns into a sustained acoustic wave.

In the low-loss window of optical fibres and at the crucial telecoms wavelength of 1550 nm, the pump and probe waves must be separated in frequency by approximately 10 to 11 GHz. The resulting compression wave induces a refractive index change that is similar to a moving Bragg grating.

Such a grating is exactly phase-matched to couple light from the higher frequency wave to the lower frequency wave. If the probe wave has a lower frequency than the pump, it will gain amplitude from the pump and grow, provided that the frequency difference exactly matches the condition for a sustained acoustic wave. If the probe has a higher frequency it will experience a narrowband loss.

Exploiting SBS in optical fibres is an ideal way to generate a narrowband gain or loss at any wavelength and with a strength determined by the pump power. For example, these resonances can be produced for any of the channels within a wavelength division multiplexing transmission system.

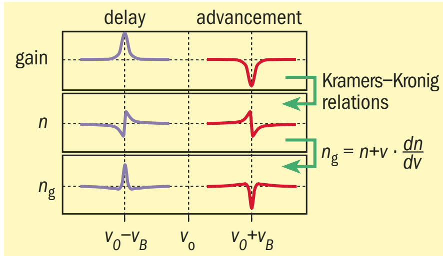


Fig. 1: relations among gain, refractive index and group index in Brillouin slow light. When a pump wave at frequency ν_0 propagates in the fibre, a probe wave propagating in the opposite direction experiences a narrowband gain if its frequency is $\nu_0 - \Delta\nu$ and a narrowband loss if its frequency is $\nu_0 + \Delta\nu$. The associated refractive index change strongly modifies the group index and thus the signal velocity at the centre of the gain/loss spectral line.

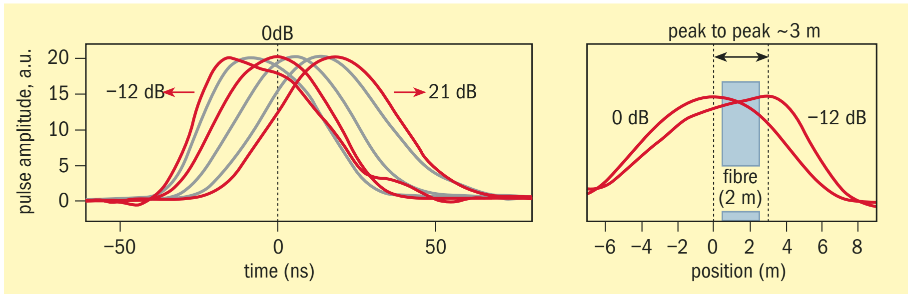


Fig. 2: measured pulse delay and advancement experienced by a light pulse propagating through a 2 m fibre for different gain or loss induced by stimulated Brillouin scattering. The inset compares the respective positions on a distance scale of the pulse propagating in normal conditions and of the most advanced pulse, demonstrating that in this case the pulse peak exits the fibre before entering it. This situation corresponds to a negative group velocity. The fibre length is represented by the shaded area.

Slow light and practical devices

In any sharp spectral transition, a refractive index change is associated with this gain/loss process and a substantial change of the group index can be observed, as shown in figure 1. This index determines the velocity of the signal envelope and can be substantially modified within a very sharp spectral transition.

For a gain process, the group index increases resulting in slow light. Conversely, a loss results in fast light. In the latter case, extreme situations may lead to a group index of less than one where the signal envelope propagates faster than the vacuum velocity of light or even at a negative group velocity. A negative group velocity means that the peak of the pulse actually exits the fibre before entering it.

This rather weird situation can be achieved thanks to a severe pulse distortion. This was experimentally and strikingly demonstrated in optical fibres by our team (*Applied Physics Letters* **87** 081113) and is represented in figure 2.

In the same paper, we demonstrate how the group velocity can be reduced to one-third of its normal value in optical fibres. At OFC2006, which was held in Anaheim, US, in March, a postdeadline paper from Southampton University, UK, detailed a four-fold speed reduction in a bismuth-oxide highly nonlinear fibre.

From the point of view of practicality, the relevant quantity is not the change induced in the group velocity of the medium, but rather the amount of fractional delay (i.e. the delay divided by the pulse length) achieved in the medium.

In an *Optics Letters* paper in July 2005, our group unveiled a way to achieve large fractional delays by simply cascading delaying fibre segments and inserting unidirectional attenuators to compensate for the large signal amplification.

A maximum delay of 152 ns was recorded using four cascaded segments, which corresponds to 3.6 times the initial pulse width. This remains the largest fractional delay obtained to date in an optical fibre, but larger values can undoubtedly be obtained by appending more delaying segments.

New challenges are now emerging to turn these so-called all-optical delay lines into practical devices. One factor is that the bandwidth is limited to the characteristic bandwidth of the Brillouin scattering, which is around 25 MHz in conventional singlemode optical fibres. Also, for a modest fractional delay of one pulse length, the power of the signal is amplified by a factor of 1000.

New techniques are being proposed to overcome these problems. For example, we recently outlined a simple scheme to overcome the bandwidth problem in Brillouin slow light (*OLE* April 2006 p11). The gain spectrum seen by the signal is given by the convolution of the pump spectrum with the characteristic gain spectrum of the Brillouin gain process. If the pump is broadened, the Brillouin gain process is also broadened and the slow light bandwidth is improved. Using this method, we can achieve GHz-bandwidth slow light by simply adding noise to the electrical input of the pump laser.

Daniel Gauthier and his team from Duke University, US, have pushed this method to the limit and reported 12 GHz-bandwidth slow light in a postdeadline paper at OFC2006. Crucially, this makes the delay line compatible with today's 10 GB/s transmission systems.

Several issues still need to be resolved before the advent of practical devices, most importantly realizing tuneable delays that do not amplify the signal by the 30 dB currently seen for one pulse width delay. The signal change must be practically maintained for any delay to make it compatible with bistable devices.

Another potential application is the all-optical buffer, which requires fractional delays much larger than those obtained so far, up to 1000 pulse widths. This means the entire data packet can be buffered and properly reordered in time.

This research topic will certainly remain very active in the coming years and must take up the challenge to shift from pure science to engineering in order to succeed. □

Luc Thévenaz is the head of the Optical Processing Group at Swiss Federal Institute of Technology in Lausanne, Switzerland. Miguel Gonzalez-Herraez is assistant professor at the University of Alcalá-Madrid, Spain. For more information, contact Luc.Thevenaz@epfl.ch or miguelg@depeca.uah.es.