# Fundamental aspects of linear slow light systems

Luc Thévenaz
*EPFL Ecole Polytechnique Fédérale de Lausanne ; Institute of Electrical Engineering,*
*SCI-STI-LT Station 11, 1015 Lausanne, Switzerland*
*luc.thevenaz@epfl.ch

In a linear slow light system the delaying process is necessarily inducing distortion for fundamental reasons, strictly bounding the maximum delay-bandwidth product to unity. Slowing the light does not directly enhance light-matter interaction, but is a corollary of the intensity enhancement by multiple interferences.

**Context**

A decade ago slow & fast light has been perceived like a very performing solution to control the timing of an optical signal, offering the yet missing photonics tool for timing control, with the ultimate objective to implement all-optical routers in telecommunications systems. It is essential that the delaying system is linear for such applications, to avoid power- and sequence-dependent timing. It has rapidly been observed that in such systems the delaying process was undermined by massive distortion when the induced fractional delay exceeds 1, i.e. when a light pulse is delayed by more than its nominal width. Experts have rapidly concluded that future all-optical routers won't certainly be based on slow light, for which other applications have been searched. Much hope has been placed in the possibility to enhance light-matter interactions, with some successful demonstrations, but here again it turns out that light slowing is not the essence of this enhancement.

**Summary**

Like in any linear system the slow light element is described by a transfer function that must ideally realize the perfect delaying function taking the simple following form $\exp(-i\omega\tau)$. This perfect transfer function shows a uniform spectral amplitude response and a linearly varying phase response. Slow light is generated using narrowband spectral resonances, for which amplitude and phase spectral dependences are related by a Hilbert transform, which translates into the Kramers-Kronig relations linking absorption to refractive index. It can be shown that a spectral resonance spanning over a limited spectrum can never simultaneously present a pure flat amplitude response and a pure linear phase response, leading to a distortion that cannot be circumvented.

Recent results have shown that the distortion can be reduced by optimizing the spectral profile of the resonance, but it can never be entirely cancelled, limiting the delay-bandwidth product to a value close to unity. This has been entirely validated by very recent experimental results.

Slow light systems are classified into 2 categories: *material* systems, in which a resonance is induced by a nonlinear interaction and optical pumping and subject to an energy transfer between the lightwave and the optical medium, and *structural* systems, in which the sharp spectral transmission change is induced by a passive structure generating multiple interferences. The most straightforward example of a structural system is the Fabry-Perot resonator.

Tuneable delays can be generated in material slow light systems, by varying the pumping power, which are active systems. Structural systems can normally not be tuned directly, since they are based on passive structures.

It has been proved that material slow light does not enhance light-matter interaction, since the excess energy density resulting from the slowing is actually entirely stored into the optical medium. On the contrary enhancement has been observed using structural slow light, since there is a direct relation between energy density and group velocity and the energy is this time uniquely present in the lightwave. This distinct behaviour proves that this is not the light slowing that strictly causes the interaction enhancement, but the light concentration through wave superposition that results in a higher intensity and has the automatic consequence to slow the group velocity.