How much can all-optical networking benefit from slow light?

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Complicated physical mechanisms or bulky configurations may limit the usefulness of tunable optical delay lines based on slow light effects.

Network designers have dreamed of all-optical networks since the late 1990s, due to their transparency to transmitted signals, superior configurability and scalability, and potentially much higher processing speed. Figure 1 illustrates a typical node in a packet-switching optical network. Based on years of research, functions such as synchronization (either bit by bit or channel by channel), switching, and, to some degree, control processing can be accomplished in the all-optical domain (although some low-speed electronics are involved as well). However, bottlenecks for all-optical networks remain, chiefly in optical buffers and routers. Tunable delay lines are essential to achieve related functional modules that would further enable reconfigurable signal processing for variable bit-rate, hybrid modulation formats, in both current heterogeneous optical communication systems and future all-optical networks.

Previously, tunable delay lines were constructed by varying a free-space or optical waveguide propagation path (i.e., a combination of pre-designed optical path lengths). Since demonstrations showing the possibilities of so-called slow or fast light as a potential enabling technology, slow-light-based tunable time delays in nonlinear signal processing have attracted considerable attention in the last few years. An overview of applications using slow-light-based tunable time delays is shown in Figure 2. In fact, most such applications are associated with optical networks or systems (e.g., regeneration, equalization, and multiplexing).

In principle, slow light is achieved by tailoring an enhanced group-index (corresponding to group-delay) resonance (around $\omega_0$) within the nonlinear medium, as shown in Figures 3(a) and 3(b). The dramatic refractive index change within the gain spectrum, illustrated in Figure 3(a), will produce a considerable effective group index change, as seen in Figure 3(b). This change is experienced by the data stream and induces a controllable group delay for the signal. Related nonlinear effects include electromagnetically induced transparency, coherent population oscillations, stimulated scattering effects (stimulated Brillouin scattering, SBS, and stimulated Raman scattering, SRS), optical parametric amplification, coupled resonator optical waveguides, and others.

Because the SBS slow light effect happens along the optical fiber itself, it is considered a promising technique for generating all-optical tunable delays. The process of SBS slow light is shown in Figure 3(c). It is based on the interaction between two counter-propagated beams inside the optical fiber: the pump light and the signal. When the pump is strong enough, and the frequencies of the pump light $\omega_p$ and the signal $\omega_s$ meet certain criteria, an acoustic wave will be generated. The signal will be amplified within a narrow bandwidth, typically tens of MHz. More important, the pump light changes the propagation constant of the signal, resulting in a significant group velocity change. Therefore, the optical pulse will be delayed by $\Delta \tau$.

However, as mentioned above, the intrinsic bandwidth of the SBS gain spectrum is limited to tens of MHz (e.g., 35MHz). In contrast, the transmission speeds of most optical communication systems today are more than 1Gbit/s. Such data signals could be severely distorted by transmission through the SBS medium...
Figure 2. Applications of a slow-light-based tunable delay line. AON: All-optical network. OC: Optical communication. OSP: Optical signal processing. HN: High nonlinearity.

Figure 3. (a) Effective refractive index change around the resonance frequency ($\omega_0$); (b) Group index (corresponding to group delay) change indicating a slow (or fast) light effect; (c) Slow light achieved through stimulated Brillouin scattering in an optical fiber.

with its narrow gain bandwidth. Because the effective SBS gain spectrum is the convolution of its intrinsic spectrum and that of the pump, researchers have proposed different schemes using a broadband SBS pump to increase the SBS gain bandwidth, as shown in Figure 4. These include directly modulating the pump laser using a pulse train, a pseudorandom bit sequence, or Gaussian noise; external phase modulation; multiple pump lines; and an incoherent pump. Therefore, most current SBS slow light schemes can accommodate signals of 2.5Gb/s or even higher.

In addition to the physics of slow light systems, we are also interested in their evaluation and demonstration because the overall performance of such modules, as well as their limitations, are of practical importance for future network development. (Related projects have been carried out by a group at the University of Southern California.3) We have investigated phase-preserving slow light transmission of 10Gb/s differential phase-shift-keying signals, and successfully transmitted spectrally efficient advanced multilevel phase-modulated formats (e.g., performed differential quadrature phase shift keying). For networking functionalities, we achieved slow-light-based multichannel synchronization, as well as a scheme of variable-bit-rate optical time-division multiplexing.

Although slow light is a potential candidate for future all-optical-networks, the current science still leaves open a legitimate question: How much can all-optical networking benefit from its use? Obvious limitations still exist, especially in bulky configurations or complicated setup. However, with progress in integrated photonics (e.g., micro-ring resonators) and emerging techniques, all-optical networks will gradually begin to take a leading role. Interest in enabling technologies for such networks based on slow light is still growing, and we are currently pursuing different approaches, as well as system optimization methods.

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References

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