The long march of slow photonics

To the Editor — It is only in the past decade that the concept of slow wave propagation has penetrated the optical domain. Slow light has already been described by many researchers as a key to advances in optical signal processing, but in this new area many puzzles still have to be solved.

A first enigma concerns the most promising approach for generating slow light. In the arena of photonic devices, ring resonators (RRs) and photonic crystals (PhCs) are duelling to become the preferred scheme. However, as the rules of this match are far from obvious, we would like to clarify for readers the issues that must be taken into account when comparing the performance of slow-light devices.

Too often the group velocity reduction (that is, the slow-down factor) is assumed to be the most important criterion, but using this alone can drive non-specialists to misleading conclusions. A large slow-down factor is not synonymous with a large absolute delay. As far as linear devices (such as delay lines) are concerned, the only benefit of the slow down is a footprint reduction: in other words, the ability of a chip-scale waveguide device to replace a long length of optical fibre. Since the origin of research into slow light, this feature has inspired dreams of large-scale optical integration, but only recently have scientists started to consider the price to be paid. Pioneering experiments have since demonstrated that a high slow down imposes severe fabrication challenges, increases sensitivity to disorder[1], and makes tunability and device control more difficult. This general result suggests that slow-light devices should be evaluated by considering a variety of figures of merit, rather than simply the slow-down factor.

First of all, the quality of the signal being slowed must be preserved. Although chromatic dispersion was initially addressed as the theoretical Achilles heel of slow light, the maximum achievable delay in state-of-the-art integrated devices is limited mainly by loss[2]. A well-known rule says that the slower the light, the higher the propagation loss[3]. However, for a generic delay line (not only a slow-light one), the key figure of merit is not the loss per unit length but the fractional loss per bit, $L_f = c\alpha/n_g B_b$, c being the speed of light, α and n_g the attenuation and the group index of the structure, and B_b the pulse (bit) bandwidth. This relation does not depend on the device's dimensions and type, or on the slow-down factor. The guiding structure with the highest ratio n_g/α will prevail.

Furthermore, to be of practical use in many applications, slow-light schemes must allow the delay to be controlled continuously, easily and reliably. It has recently been demonstrated that these requirements are all fulfilled by a reconfigurable coupled resonator optical waveguide (CROW)[2]. In a CROW, the higher the storage efficiency η_s (how many bits are delayed by each resonator), the simpler is the reconfiguration. This allows a minimum number of resonators to control the delay. The unitary time delay induced by every resonator is simply $1/\pi B$, with B the CROW bandwidth: as a result, η_s depends only on the ratio B_b/B and not on either the resonator dimensions and type, or the slow-down factor.

On paper, a reconfigurable CROW may be realized by using either RRs or PhCs. At signal rates of tens of gigabits per second, the best results have been achieved in RR CROWs, and recently an optical delay line has been described[2] that is capable of delaying continuously an entire byte (eight bits), while preserving signal quality. The device, made of eight RRs in medium-index-contrast glass, introduces 0.5 dB attenuation per bit delay and can be easily controlled thanks to the high storage efficiency (η_s = 1 bit per RR) and its moderate slow-down factor (about 5). State-of-the-art PhC CROWs have larger bandwidths and smaller absolute delays, even in case of impressive slow-down factors (>100)[4], and seem to be more suitable for applications at higher bit-rates. For instance, Notomi *et al.*[4] recently used a PhC CROW with 60 cavities to delay a 12.5 Gbit s^{-1} data stream by 80 ps (1 bit delay) and, more effectively, a PhC CROW with 150 cavities to delay a 21-ps-long pulse by 125.3 ps (5.8 bits). Owing to the small storage efficiency of these structures (η_s << 1 bit per resonator), every pulse spreads over several tens of cavities, thus making the dynamical control of the delay still an open question. By following a different approach, Baba and co-workers have demonstrated that a chirped PhC waveguide can be used to tune the delay of 1.2-ps-long pulses over nearly seven pulse lengths[5]. This confirms the feeling that slow light in PhC structures is especially promising for ultra-wideband applications (terabits per second or more), where small absolute delays are of interest.

Manipulation of a single byte is a fundamental milestone in the long march of slow light towards the advanced processing of optical information[6]. Although RRs and PhCs have been walking along parallel roads, the hope is that this competition will soon converge into cooperation. From this point of view, silicon-on-insulator technology could offer a common platform for the integration of compact RRs[7] and PhC structures. Could PhCs embedded in RRs be the new frontier of slow photonics? ❐

References

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