# Slow light - perspective and applications

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The phenomenon of slow light is discussed, with a focus on slow light structures based on photonic crystals. Slow light offers field enhancement for increased nonlinear interaction, phase enhancement in devices such as Mach-Zehnder modulators and the possibility of controllable delay time. We believe that bandwidth is a key parameter and have now demonstrated a slow light structure that can accommodate 2.5 THz of bandwidth. Furthermore, slow light can only be useful if it is not compromised by losses. Due to recent improvements in our technology, we can now achieve losses of order 4 dB/cm, which is amongst the best reported for single mode photonic crystal waveguides.

**Keywords:** Slow light, photonic crystals, optical waveguides

## Introduction

The phenomenon of slow light has captured the imagination of many researchers in the last few years because it offers an important level of control over light-matter interactions. So far, the slowdown of light has mainly been pursued in atomic media, most notably via electromagnetically induced transparency (EIT), but also in semiconductors featuring population oscillations, nonlinear gain and loss characteristics as well as in fibres. More recently, slow light has also been demonstrated in dielectric structures, especially coupled ring resonators [1,2] and photonic crystals [3] and it is the latter that this paper is focused on.
The keen interest in slow light in dielectrics is motivated by the fact that slow light adds functionality to a material by structuring alone. This is of great interest, as it allows the enhancement of the typically weak light-matter interaction in optical materials. Linear effects such as gain, thermo-optic and electro-optic interaction scale with the slowdown factor, whereas nonlinear effects may scale with its square [4]. An alternative to the slow light approach is to use cavities for such increased light-matter interaction, a topic that is widely studied in the photonic crystal community. In comparison to cavities, slow light structures offer additional control over the spectral bandwidth of the light-matter interaction and the phase change achievable in a device. This phase argument is explained in fig. 1 below.

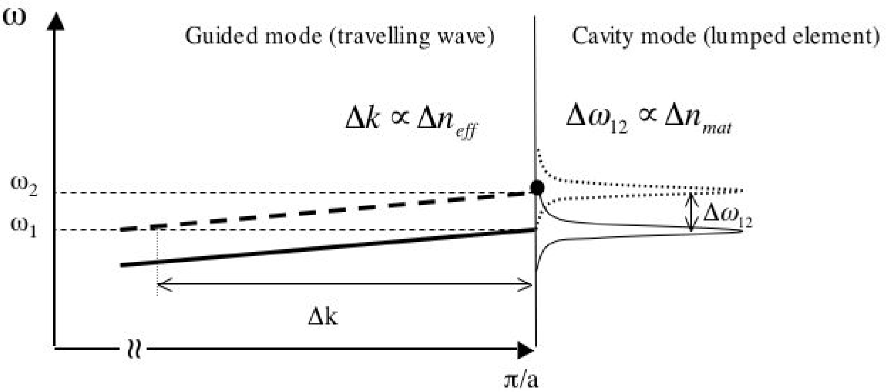


**Figure 1.** Idealised dispersion curve of a waveguide in the slow light regime. The solid curve represents the original dispersion curve, whereas the dashed line represents the same curve after application of a refractive index change $\Delta n_{mat}$.

The phase change in an interferometric device, such as a Mach-Zehnder interferometer, is enhanced in the slow light regime because the Mach-Zehnder response depends on Δk, i.e. the change in effective index $\Delta n_{eff}$, not just the material refractive index change $\Delta n_{mat}$. If a refractive index change is applied to the device, the dispersion curve shifts correspondingly. In the cavity, the same shift in material index corresponds to a shift in the resonance, as illustrated by the two resonance curves on the right of the figure. Because of the small slope of the curve, i.e. its low group velocity, a small $\Delta n_{mat}$ results in a large Δk. Therefore, even devices that operate on a phase change can benefit from a low group velocity.

**Bandwidth**

While slow light in photonic crystals has already been observed several years ago [5], the operating point is typically on a near-parabolic dispersion curve near the edge of the Brillouin zone. Therefore, slow light in photonic crystals tends to coincide with high dispersion, which removes most of the advantages of operating in the slow light regime and severely limits the bandwidth that can be utilised. This is not an intrinsic property of the structure, however, but subject to design. As shown recently [6,7], the appropriate choice of structure and careful design allow us to design structures with moderate slowdown factor (group indices in the range between 10-100) and bandwidths of several nanometres in wavelength at 1550 nm, corresponding to a THz or more. Although higher slowdown factors have already been demonstrated [3], the corresponding penalty is a reduction in bandwidth. For applications in all-optical signal processing, bandwidth is a key concern, as this is the main advantage of Optics over Electronics. Designing optical structures that limit the bandwidth to the MHz or low GHz regime, such as very high Q cavities, therefore does not seem to be advisable.

**Losses**

Losses are another critical issue. It is essential to build slow light devices on the basis of very low loss devices; otherwise, any benefit deriving from the slow light operation may be lost. It is therefore remarkable that photonic crystal waveguides exhibiting losses in the few dB/cm range have now been demonstrated, which is close to the values reported for photonic wires.

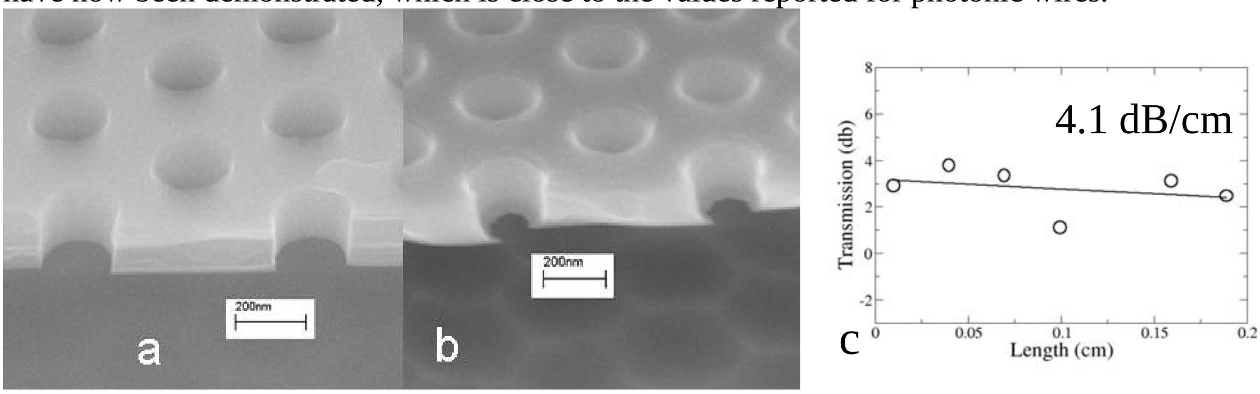


**Figure 2.** Cross-section of a Si airbridge after etching, highlighting the sidewall profile of the photonic crystal holes. a) Etching quality of very low loss waveguides (<10db/cm), b) Etching quality of higher loss (here: 105 db/cm) waveguides, featuring small rims at the bottom of the hole - the etch depth being fractionally too small. This results in the formation of a lip or rim at the bottom of the hole, which scatters light very strongly. In addition, such defects are also prone to large variations from hole to hole, which causes disorder, further increasing the scattering loss. c)

Transmission versus W1 waveguide length at a wavelength of 1.52 µm. The slope is 4.1± 0.9 db/cm [8] which is near the best value reported worldwide [9].

The next question is how losses scale with the slowdown factor. There have been suggestions that there is a square dependence of the loss on the slowdown factor, i.e. losses scales as $1/n_g^2$ [9]. While this is certainly the case for the type of waveguide with a pararabolic dispersion curve operating near the band-edge as discussed earlier, there are indications that a slow light design operating away from the bandedge has a more favourable dependence [7].

## Discussion and Conclusion

In a photonic crystal, the phenomenon of slow light is created by the resonant interaction of the guided mode with the periodic lattice, resulting in the formation of a slow moving interference pattern (the "slow mode"). By controlling this interaction between the incoming mode and the lattice, it is possible to control the resulting slowdown factor and the bandwidth over which it occurs to the extent that slow light devices with THz bandwidth have now been demonstrated. Any all-optical device has to accommodate a sizeable bandwidth in order to compete with the electronic approach The typical bandwidth achieved with photonic crystals, namely 100's of GHz or even THz, is therefore an essential requirement, compared e.g. to slow light based on atomic resonances as in electromagnetically-induced transparency [10]. Hence, we believe that broadband and slow light enhanced all-optical functions such as switches and modulators are the most likely outcomes of this research. Optical memory, which is another function proposed for slow light devices, is more difficult to achieve, since even with the losses of order few dB/cm discussed above, storage times in the nanosecond regime are difficult, which would allow the storage of a few bits of information only. Such storage would also require tunability of the slowdown factor, which is more difficult to achieve in photonic crystal-based devices than, for example, in EIT or in systems based on semiconductor optical amplifiers (SOAs).

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