

Silicon slow light photonic crystals structures: present achievements and future trends

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Abstract Slow light in planar photonic structures has attracted for some years an increasing interest due to amazing physical effects it allows or reinforces and to the degrees of freedom it raises for designing new optical functions. Controlling light group velocity is achieved through the use of periodical optical media obtained by nano-structuration of semiconductor wafers at the scale of light wavelength: the so-called photonic crystals. This article reviews present achievements realized in the field of slow light photonic bandgap structures, including the physical principles of slow light to the description of the most advanced integrated optical devices relying on it. Challenges and current hot topics related to slow light are discussed to highlight the balance between the advantages and drawbacks of using slow waves in integrated photonic structures. Then, future trends are described, which is focused on the use of slow wave slot waveguides for non-linear optics and bio-photonic applications.

Keywords slow light, photonic crystals, silicon photonics, integrated optical devices

1 Introduction

Silicon photonics has received a considerable interest for some years. The motivation for this was primarily related to the bottlenecks of metallic interconnects in silicon chips [1]. Since then, the possible application fields of silicon photonics has widen significantly. Regarding optical interconnects, optics is no more seen only as a possible solution to guide the signals with reasonable loss and

distortion, but also as a viable solution for signal processing. All-optical functionalities like information storage, logical optical gates, have emerged at the research level and are likely to bring solutions for future silicon chips¹). Anyway, an important point in this evolution is the fact that integrated optics can rely on the same materials and similar technological steps as microelectronics, through the use of the now well-established silicon on insulator (SOI) photonic technology [2]. Current evolution shows that optics is likely to enter chips in a very near future. IBM and the Intel Corporation have been responsible for strong achievements in the recent period. Among their key results, Intel's researchers demonstrated for the first time, in 2004 a silicon optical modulator with a cutoff frequency higher than 1 GHz [3,4]. Since then, further progress has been achieved and frequency bandwidths of present state-of-the-art silicon modulators have progressed up to 40 Gbit/s [5–7]. Other results were also published about optical lasing and amplification using the Raman effect in silicon nanowaveguides [8,9]. More recently, IBM research announced a new technology developed for dense integration of electrical and optical devices on a silicon chip²). This technology is presented as a possible solution to change the way how computer chips talk to each other — they can use pulses of light rather than electrical signals that is a potentially cheaper, faster and less power consuming approach than electrical communications via copper wires and cables. In addition to the field of optical interconnects, silicon photonics is now seen as a universal technology for various other applications related to sensors and bio-photonics. The motivation for this is the disposal of large and low cost wafers and the possible fabrication of optical integrated structures, with a mature processing technology, to probe molecular entities or biological materials. The rich panel of

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1) Intel milestone confirms light beams can replace electronic signals for future computers. http://www.intel.com/pressroom/archive/releases/2010/20100727comp_sm.htm

2) Silicon integrated nanophotonics. http://domino.research.ibm.com/comm/research_projects.nsf/pages/photronics.index.html

photonic structures, including waveguides and integrated cavities and resonators, can be exploited in this purpose.

One of the key aspects of all of these recent achievements arises from the strong confinement of the electromagnetic field in silicon waveguides, which itself is a consequence of the strong index contrast between the waveguide core (silicon: $n \approx 3.48$ around $\lambda = 1.55 \mu\text{m}$) and cladding (silicon dioxide: $n \approx 1.44$ around $\lambda = 1.55 \mu\text{m}$). Typical dimensions of single-mode SOI strip waveguides are around $200 \text{ nm} \times 400 \text{ nm}$, meaning a cross-section around $0.08 \mu\text{m}^2$. If compared with optical fibers or silica on silicon waveguides, this represents a waveguide cross-section decrease by a factor of 800. Strong field confinement leads to strong optical intensity, which in turns is responsible for reinforcing a vast panel of physical effects including the free carrier dispersion effect, non-linear optical phenomena for Raman amplification [8,9] or parametric amplification [10], and interaction with polymers [11,12] or biological materials [13,14].

Nevertheless, further increase of optical intensity is still desirable in many situations to reinforce the physical effects and shrink the device dimensions. To illustrate this, the example of silicon optical modulators can be considered. Most of Gbit/s optical modulators exploit a Mach-Zehnder interferometer to convert the carrier plasma-induced effective index modulation into an intensity one [3,4,6,7]. The typical footprint of such components scales a few millimeters due to the rather low effective index modulation by carrier depletion in PN junctions. Slowing down the light passing through the active region of the modulator allows strengthening the interaction between light and matter proportionally to the light group index. Considering a slow wave group index around 100, this means a device size reduction typically by a factor of 30, i.e., shrinking the Mach-Zehnder footprint below $100 \mu\text{m}$. The same conclusion also holds for most of other effects, including non-linear effects that scale as n_G^2 [15]. Self-phase modulation, two-photon absorption, third harmonic generation, and so on, are among the related non-linear optical phenomena that can be exploited for the design of all-optical signal processing devices of future silicon chips.

In this article, current issues related to slow light are reviewed, and a description of future trends is made. First, the physical origin of slow light in planar photonic bandgap structures is briefly reminded and dispersion engineering of slow light modes is presented in Sect. 2. Section 3 is devoted to the loss issues in slow light structures and a description of coupling issues to slow light structures. Experimental characterizations of slow light structures are described in Sect. 4. Recent advances towards optical components are reviewed in Sect. 5, while Sect. 6 gathers some future trends related to slow light waveguide structures.

2 Dispersion diagram engineering for slow light

The most powerful concept to understand the physical properties of photonic crystal is the dispersion diagram $\omega(k)$, ω and k being the light frequency and wavevector, respectively. In analogy to the physics of semiconductors, the primary property of PhCs is the possible existence of a bandgap frequency, related to the fact that in given frequency ranges, the interference pattern between forward and backward waves leads to the destruction of any propagation mode. Planar PhCs obtained by etching of a hole periodical lattice are not truly periodical media, as periodicity is broken in the vertical direction. The situation under interest is depicted in Fig. 1. Optical confinement is achieved vertically through the total internal reflection mechanism, while optical propagation in-plane is governed by the lattice periodicity. Due to the scalability of Maxwell's equations, normalized frequency can be introduced as $\omega = a/\lambda$, with a the PhC lattice period and λ the optical wavelength in vacuum. As seen in Fig. 1(a), two light polarizations are possible, namely the transverse electric-like and the transverse magnetic-like ones. In the considered case of a triangular lattice of air holes in a silicon slab waveguide with a 30% air filling ratio, a large bandgap is opened in transverse electric (TE)-like polarization. Introducing a linear defect by removing a single row of holes in such a configuration leads to the so-called $W1$ waveguide (Fig. 1(c)). This defect appears in the projected $\omega(k)$ dispersion diagram along the defect direction by optical modes appearing in the PhC bandgap, as shown in Fig. 1(d).

From a practical point of view, optical modes situated below the silicon oxide light line must be used, as they are strictly confined in the vertical direction by the TIR mechanism. Considering also the requirement of even symmetry of the field for efficient coupling from strip waveguides, the lowest frequency optical mode in the frequency bandgap around $\omega = 0.24$ depicted in Fig. 1(d) has the typical shape of PhC modes that can be used to ensure slow light propagation. Its properties, which come from both the index guided and the bandgap guided mechanisms, have been described in Ref. [16]. Due to nearly identical amplitude of the forward and backward plane waves constituting the Bloch of the 1D PhC line defect, an almost standing wave appears at least near the band-edge of the first Brillouin area. Quantitatively, Bloch wave group velocity is given by $v_G = \partial\omega(k)/\partial k$, meaning that flat band is required to slow the light beams. Figure 1(d) shows such a configuration for the even parity low frequency optical mode located into the bandgap. The group index n_G is defined as $n_G = c/v_G$ ($c = 3 \times 10^8 \text{ m/s}$) or $n_G = 1/v_G$ if normalized unities are used for v_G . At the band edge of PhC guided modes, n_G can have arbitrary high

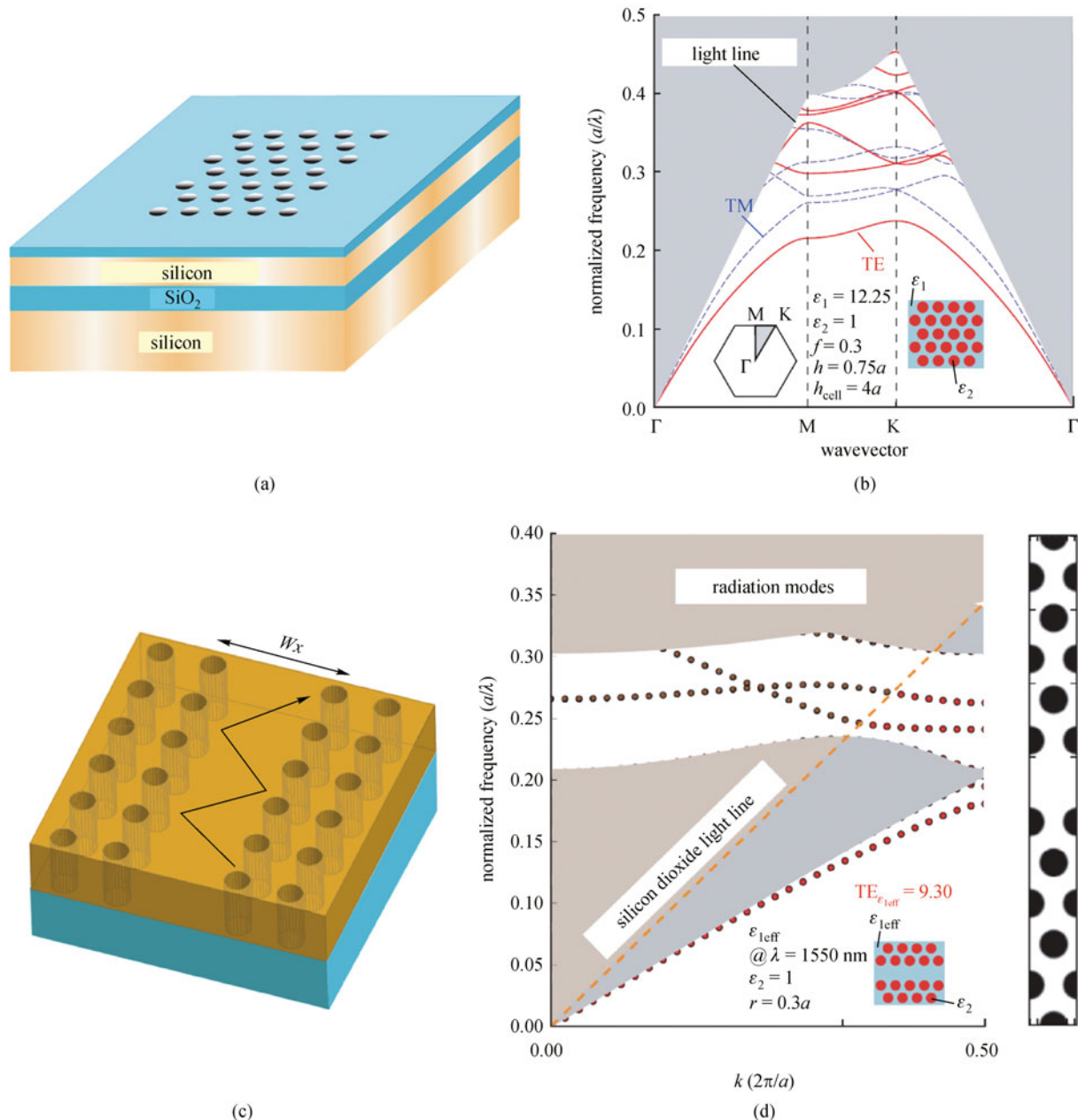


Fig. 1 Optical guided modes in a silicon on insulator planar photonic crystal. (a) Schematic picture of SOI 2D planar PhC; (b) typical dispersion diagram calculated with 3D plane wave expansion method, grey region corresponds to radiation modes, i.e., electromagnetic modes that are not strictly confined within the optical slab; (c) schematic picture of a W1 PhC planar waveguide; (d) associated dispersion diagram with projection of light wavevector in the direction of the linear defect. Normalized quantities are used for both wavelength and wavevector [16]

values, but as seen hereafter, ultra-large n_G values above 100–200 are extremely challenging from a practical point of view.

Starting from the initial qualitative requirement of flat band, significant results have been performed in the recent period to engineer flat bands with respect to some requirements. Among these requirements, the two main ones are the ‘slow light bandwidth’ and the induced group velocity dispersion (GVD). Slowing down optical guided waves is indeed perceived as useless if the associated bandwidth shrinks to extreme low values in the same time,

while large GVD values can also lead to strong pulse distortion in time domain. In Ref. [17], Frandsen and co-workers proposed the concept of semi-slow light PhC waveguides. By engineering the hole radii of the first and second row of holes with respect to the central line of a W1 PhC waveguide, they demonstrated light guiding by the bandgap mechanism with group index around 34 in a 11 nm bandwidth with GVD β_2 parameter below $10^6 \text{ ps}^2/\text{km}$. Their idea, retained in later works, was to obtain a constant group index frequency range by engineering the electromagnetic field penetration within

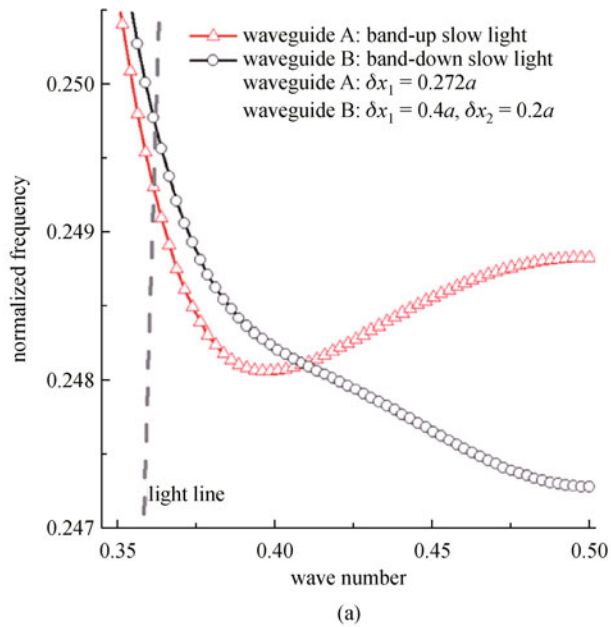
the PhC lattice in the slow light regime, due to the increased field spreading when propagating with low group velocity. In other works, shifting the two first row of holes was proposed to keep constant hole radius within the PhC and minimize the constraints over technological fabrication, but keeping the same idea to tailor the $\omega(k)$ relationship to manage a constant n_G over the largest bandwidth as possible [18,19]. n_G around 49 with a 9.5 nm bandwidth was typically obtained. With respect to TIR waveguides, for which group index is around 3–4, such group index values represent an increase by a factor or typically 15.

In a couple of two papers [20,21], we proposed and studied new waveguide geometries to enlarge the possible bandwidth for a given constant group index value. Quantitatively, this turns into optimizing the delay-bandwidth product (DBP) of photonic crystal slow light waveguide modes. This factor of merit is a good indication of the highest slow light capacity that the device potentially, being defined by

$$DBP = \tilde{n}_g \times \frac{\Delta\omega}{\omega}. \quad (1)$$

In this relationship, the average group index is calculated by

$$\tilde{n}_g = \int_{\omega_0}^{\omega_0+\Delta\omega} n_g(\omega) d\omega / \Delta\omega. \quad (2)$$



Starting from a *W1* PhC waveguide, we showed that shifting the neighbouring rows of holes with respect to the waveguide center in the direction of light propagation (as shown in Fig. 2(b)) allowed a fine tuning of the PhC slow light mode (Fig. 2(a)).

Using this strategy and including all possible opto-geometrical parameters like the silicon slab thickness, the hole radius, the waveguide width, the lattice compression, and stating a target group index around 90, a bandwidth around 6.4 nm for $\pm 10\%$ constant n_G was obtained [21]. The related normalized delay bandwidth product (NDBP) around 0.35 appeared to be larger than all other previous results, and near the theoretical maximum value around 0.4, as explained in Ref. [21]. For reference, a non-engineered *W1* waveguide has an NDBP factor around 0.020 for the same average $n_G=90$. In the same time, the designed waveguides proved to be extremely robust with respect to GVD-induced pulse distortion. Due to the local condition of nearly-flat n_G curve with wavelength, GVD β_2 parameter below 10^3 ps²/km was obtained in the full useful bandwidth, with zero-dispersion near the bandwidth center.

3 Slow light loss issue

Optical loss in slow light PhC waveguides is probably the strongest problem for any practical use and possible applications. While GVD-induced distortion and bandwidth issues have to be taken into account, satisfying

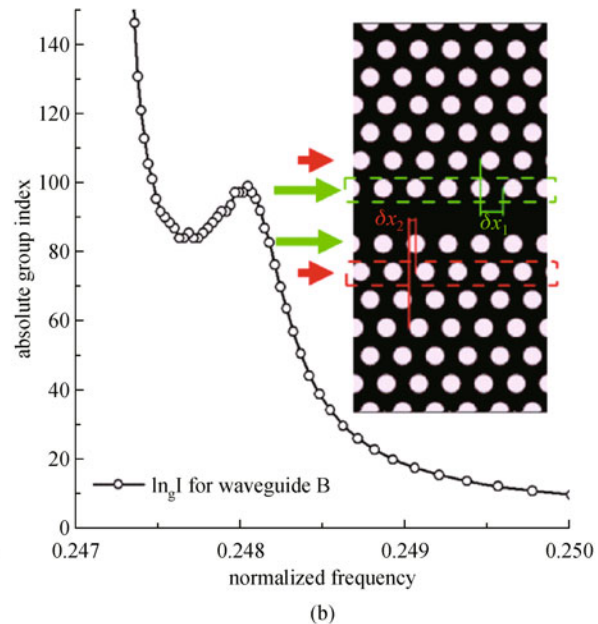


Fig. 2 Dispersion engineering of *W1* modified PhC waveguides. (a) Dispersion diagram associated with waveguide geometry depicted in the inset of the figure right part; (b) group index related with so-called waveguide B, characterized by δx_1 and δx_2 shifts with respect to light propagation direction

solutions can be found using a proper dispersion engineering methodology, as stated just above. The same conclusion can be hardly given for propagation loss issues.

Using slow light in photonic crystal structures raises two main issues. Figure 3 shows a schematic picture of the possible sources of light leakage and losses for practical applications. The first one is related to propagation losses, and the second one is related to coupling-induced losses. These two problems are described hereafter in two different sub-sections.

3.1 Extrinsic losses

Optical propagation losses in PhC waveguides can be classified in intrinsic and extrinsic losses, respectively. Intrinsic losses, that correspond to coupling of propagation modes with radiating modes located above the cladding light line, can be quite easily removed, especially in strong index contrast slabs like SOI ones. Extrinsic losses correspond to scattering of waves due to imperfect fabrication and surface roughness of the planar photonic crystals, and cannot be eliminated. At the present state-of-the-art of silicon clean room technologies (in particular e-beam lithography), root mean square roughness/disorder is around 2 nm. Propagation loss induced in optical SOI waveguides already exist in strip waveguides based on the TIR guiding mechanism [22,23]. Disorder/roughness is classically described with a correlation length, in addition with RMS roughness. This length, which represents the characteristic length over which defects are correlated each ones to others, depends on the employed fabrication techniques, but is typically about 50–100 nm [23]. Improvement of technology is likely to occur in the following years. Yet, the problem of losses in slow wave guided structures reveals a fundamental nature: as waves travel with low group velocity, light intensity, or electromagnetic density, is extremely high. While this is an advantage for enhancement of non-linear phenomena [24], this is obviously a drawback for extrinsic loss issues.

Important implicit question is the following: does it worth slowing down light if low group velocity waves suffer from significantly enhanced losses? In another way:

slowing down light beams allows a kind of space folding, but are overall optical extrinsic losses in this case lower or stronger than if a larger distance would have been considered with propagation of fast waves? This question has generated some debate in recent years. Only recently, a comprehensive study has been published about this issue [25]. To summarize previous discussions, the first question was to estimate the dependence of extrinsic losses α (dB/cm) as a function of n_G . In some works, a n_G dependence was proposed while in other ones a n_G^2 was stated. The most recent reply to this question is that both answers are correct. The $\alpha = \alpha(n_G)$ law depends in fact on the involved scattering mechanisms. The two main scattering mechanisms involved in extrinsic losses are the out-of-plane and back-scattering scattering mechanisms. While the first one involves scattering from the guided mode to a continuum of radiating modes, the second one involves the scattering between the forward guided mode and the reverse identical one. For this reason, loss corresponding to the first mechanism scales as n_G , while loss scales as n_G^2 in the second case. Interestingly, what was recently shown is that extrinsic loss is primarily dominated by the out-of-plane mechanism for low n_G values, while above some n_G threshold value, loss is dominated by the back-scattering mechanism. The analysis is even a little bit more complicated as multiple back-scattering mechanisms are also to take into account. Overall, the best state-of-the-art engineered PhC slow light waveguide has 100 dB/cm of extrinsic losses for light propagation at $n_G = 50$ [25]. Such values give the best time delay per nanosecond if compared with strip waveguide ring resonators or any other classical TIR waveguiding structure. The answer to the above question is thus that PhC slow light structure suffer from strong extrinsic losses, but they allow shrinking device dimensions, and overall allow obtaining larger time delays than unfolded waveguide structures. Increasing light group index above 100 or 200 is possible through *over-engineered* design, but leads in practice to losses above 200–500 dB/cm. Such a loss level may be acceptable in some cases, when propagation length is short.

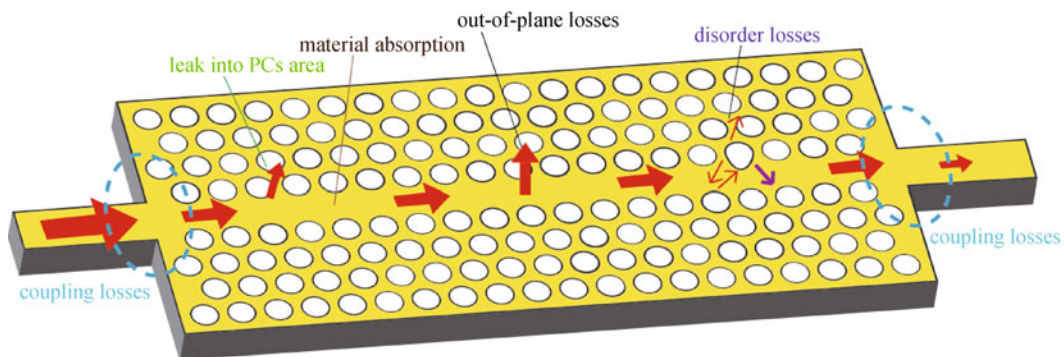


Fig. 3 Schematic picture of different origins of light leakage and losses in slow light photonic crystal waveguides

3.2 Coupling issue

Light coupling from strip access input/output waveguides is another problem that has to be faced when using slow waves. The reason for this stems from the strong group index and field profiles mismatches between the fast incoming optical mode propagation and the slow optical mode propagation into the PhC waveguide, as shown in Fig. 3. Light group index into strip waveguides is typically around 3–4, while slow optical modes up to $n_G = 100$ can be met. Considering similar fields on both waveguides, which is clearly not the case and which even worsen the situation, the power reflection coefficient between two different waveguide sections can be estimated as $(n_{G2} - n_{G1})^2 / (n_{G1} + n_{G2})^2$, n_{G1} and n_{G2} being the two considered group indices [26]. A simple estimate shows that overall I/O coupling loss is around -16 dB in this example case. Many works have been devoted to solving this coupling issue. Among the main strategies, the first one is based on a gradual transition between fast and slow waves [27], the second one makes use of $\lambda/4$ -like PhC anti-reflection coating [28], while the third one relies on exploiting evanescent modes at the interface between both kinds of waveguides [29,30]. In particular, de Sterke and co-workers showed that efficient coupling between fast and

slow photonic crystal waveguide modes is possible, provided that strong evanescent modes exist at the interface to match the waveguide fields across the interface [30]. Evanescent modes are especially required when the propagating modes of the two waveguide sections have very different modal profiles. This approach is case-sensitive, as results may change a lot from one PhC waveguide to another, but can help injecting light into ultra-low group velocity down to at least $c/400$.

Figure 4 shows the input/output tapers we proposed to minimize the overall strip/W1 coupling losses by slowing down light group velocity. The even TE-like exploited optical mode is depicted in red in Fig. 4(a), showing also the PhC mode fields for the even and odd modes at several wavevector values. The main idea of the taper is starting at normalized frequency $\omega = a/\lambda$ at point 3 corresponding to fast waves, and decreasing to point 4 and 5 to slow waves in a few lattice periods. The related group velocity curve is shown in Fig. 4(b), where initial and final v_G values are given. Maintaining the operating wavelength around 1600 nm, the ω decrease is obtained by enlarging the lattice parameter itself, as shown in Fig. 4(c).

Using this approach, we showed that for an optical mode with a group index of 19, the overall input strip to output strip transition can be enhanced from 18% without tapers

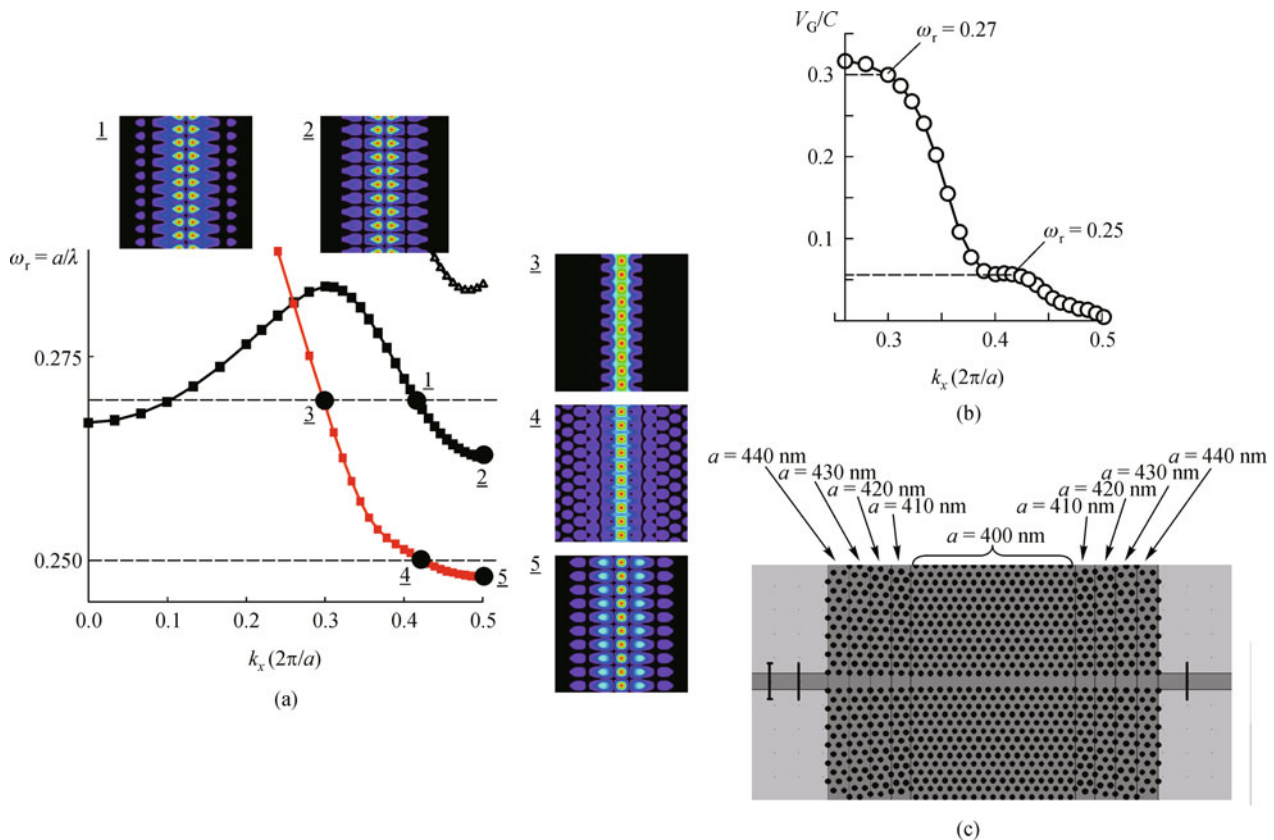


Fig. 4 Design of input/output tapers for light injection/collection into/from strip waveguides to slow light PhC waveguide mode. (a) Dispersion relationship of the considered linear defect mode; (b) light group velocity of the even mode depicted in red curve of (a); (c) schematic picture of the gradual taper introduced at both interfaces between strip and PhC waveguides

to 95% with a 3.4- μm -long taper on each side of the PhC waveguide. Such a result is also a proof that the gradual approach of light coupling into slow wave modes is not necessarily made at the expense of device compacity.

4 Experimental characterizations of slow light structures

As stated just after, optical characterization of slow wave propagation in guided wave devices is not straightforward. Several methods are possible for this. One of the possible ways to classify them is to distinguish time-domain and frequency-domain methods.

Time-domain methods aim at characterizing the slow wave propagation by direct experimental evidence. Gersen and co-workers succeeded in using a near-field optical scanning microscopy technique to probe ultra-slow light in PhC waveguides [31]. They demonstrated the real-space observation of slow wave propagating pulses by monitoring the local phase and group velocities of modes. In this experiment, movement of electromagnetic field was almost not discernable during at least 3 ps, corresponding to optical mode propagation with group index above 1000. In another work, Asano and co-workers applied a time-domain measurement of light pulse propagation by an auto-correlation technique [32]. Using this method, the authors estimated the light time of flight between the two sides of the Fabry-Perot cavity formed by the two interfaces of the PhC slow light waveguide and input/output strip optical waveguides. Then, light group index was deduced from the measured time of flight values. Jacobsen and co-workers also developed another method, based on the measurement of the phase delay of the transmitted signal as a function of wavelength [33]. Considering that the transmitted signal after the slow light PhC waveguide is an envelope function for the amplitude of the light, the authors noticed that the envelope phase velocity corresponds to the group velocity of light. Amplitude-modulated light was thus injected into the PhC waveguide, and the envelope phase was recorded as a function of wavelength. With this approach, the authors demonstrated experimental evidence for slow waves up to $n_G = 230$, in good agreement with numerical simulations. Other authors still employed another method to characterize slow waves in integrated devices. Imhof and co-workers used a phase-sensitive ultrashort-pulse interferometric technique on their side [34]. The principle of the method is to measure the interferometric cross correlation function of a short optical pulse transmitted by the slow wave waveguide. The cross-correlation signal contains several informations about the propagation of light pulses, including the group index and the GVD parameter.

Frequency-domain methods can also be applied. The basic idea of these methods is to obtain information about the light group index by monitoring the transmission

spectrum of simple interferometers like the Fabry-Perot cavity or the Mach-Zehnder interferometer. A typical example of this method can be found in Ref. [35].

Figure 5 shows a PhC device implemented in our group to characterize slow waves, as well as the related transmission spectrum and group index curve with wavelength.

An integrated Mach-Zehnder interferometer was considered, with a reference arm and the PhC slow light waveguide inserted in the other arm. The interference pattern comes from min-to-max or max-to-min, when a π phase shift is accumulated by wavelength increase. Approaching the slow regime of the PhC waveguide, the frequency band tends to be more and more flat, meaning that a large wavevector shift Δk is obtained by a small wavelength increase. As the relative phase shift $\Delta\varphi$ between the two arms scales as $\Delta k \times L$, with L the PhC waveguide length, the larger n_G the easier the accumulation of an additional π phase shift. Quantitatively, the PhC group index can be estimated using the following relationship [35]:

$$n_G^{\text{signal}}(\lambda) = n_G^{\text{ref}}(\lambda) + \frac{\lambda_{\min}\lambda_{\max}}{2L|\lambda_{\min} - \lambda_{\max}|}, \quad (3)$$

where λ_{\min} corresponds to a transmission minimum and λ_{\max} to a transmission maximum.

Although not so straightforward as time-domain ones, such methods also provide experimental evidence for slow light propagation in PhC waveguiding structures and can be implemented with similar experimental setups as those required to characterize other optical integrated devices.

5 Towards slow light optical devices

Implementing slow light devices to shrink device dimensions or reinforce physical effects, such as non-linear optical mechanisms, has been proposed for years. Yet, the number of practical devices implementing such effects has not been so large up to now. This is probably due to the difficulty of simultaneously managing the loss, the dispersion, and the bandwidth issues. Works collected in the last six years have yet paved the way for future promising concepts and devices involving slow light. In 2005, Jiang and co-workers published an 80 μm interaction length PhC modulator demonstrated in silicon [36]. The optical modulation mechanism, based on the carrier plasma effect, was significantly reinforced due to the extraordinary flat PhC dispersion curve. A PN junction was integrated to inject the free carriers required to modulate the local refractive index. A modulation depth of 92% was obtained, with a low frequency response in this first non-optimized device. Further progress allowed later to increase the frequency operation to 1 Gbit/s [37].

More recent works have been focused on the integration of other materials with silicon to enlarge the panel of

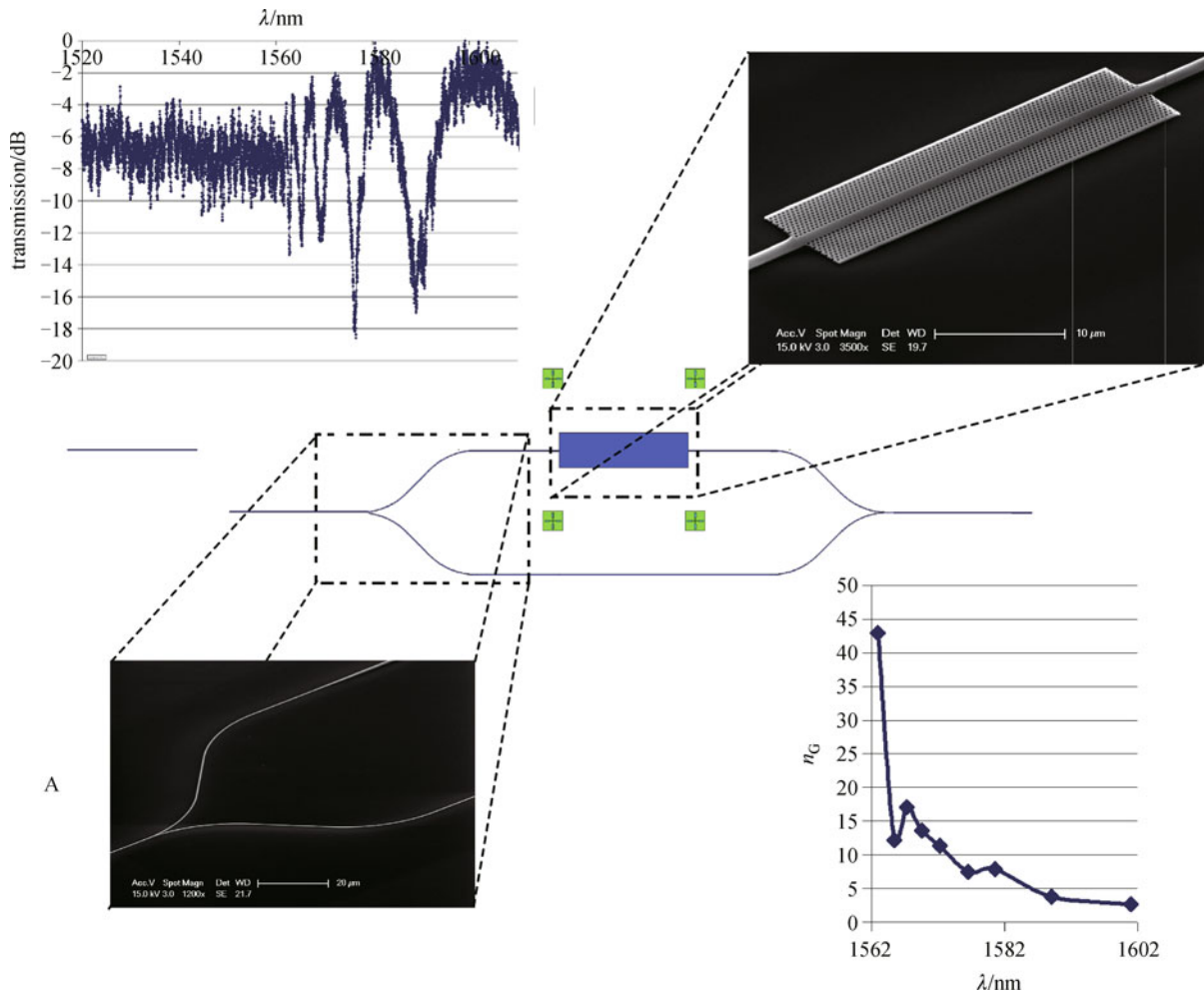


Fig. 5 Frequency-domain measurement of the group index of a PhC waveguide in a Mach-Zehnder configuration. PhC waveguide is inserted in one of the two arms of a Mach-Zehnder interferometer. Experimental transmission spectrum has typical cosines shape, but narrowing of the min-to-max or max-to-min transmission near band edge is the signature of increasing n_G values

physical effects available for light modulation and detection, owing also to the fact that electro-optic effects in silicon are known to be low [2]. In particular, recent works have focused on the use of a new kind of slow wave PhC waveguides combining the possibility to fill the waveguide core (slot waveguide) and slowing down the light, leading to the so-called slow light slot waveguides. Slot waveguides based on the TIR mechanism were introduced by Almeida and co-workers [38]. In such waveguides, a thin (50 to 200 nm) slit is introduced at the center of the waveguide core. Due to the discontinuity of the normal component of electric field, a non-negligible fraction of the electromagnetic energy around 30% can be confined within the slot, i.e., in the low index fillable slit. This property constitutes the main advantage of slit waveguides that can be filled with non-linear optical, electro-optical, or biological materials. Due to the small dimensions of SOI nanowaveguides, optical intensity within the slit is already extremely high, around some tens of μm^{-2} [38]. In the continuity of these works, combining these slot waveguides with concepts coming

from the slow wave PhC waveguiding mechanism was further proposed [39]. The main advantage was to make the in-slot electromagnetic density increase due to slow wave propagation. Brosi and co-workers proposed a thorough design of an optical modulator based on the infiltration of an electro-optic polymer into the slit of a PhC slot waveguide [40]. The authors demonstrated the possible use of this approach to design a 1V optical device, with an active length of 80 μm thanks to slow wave propagation, and with a 100 Gbit/s bit rate due to extremely fast electro-optic modulation and resistor-capacitance (RC) device optimization. The slot width considered in this work was 150 nm. Recent works experimentally demonstrated the concept by enlarging the slot width to 320 nm to facilitate its filling with polymers, at the expense of electromagnetic field intensity. A modulation factor of merit $V_\pi L_\pi$ around 4.4 V·cm was obtained [12]. Improvements in the integration of active or electro-optic materials in slow light slot PhC waveguides is thus likely to occur in a near future.

One of the challenging issues in this direction is the

possibility to enlarge the waveguide void to facilitate the slot filling, while maintaining an ultra-high optical intensity to favours the interaction between the electromagnetic field and the introduced low index material. We recently proposed for this a new kind of slot PhC waveguide [41]. With respect to previous works related to slot PhC waveguides, we propose introducing a Bragg-like corrugation within the slit itself. Figure 6(a) shows a schematic picture of the proposed approach, highlighting the main opto-geometrical parameters. A Bragg-like corrugation of the slit width with the same lattice period as the one of the PC is introduced. Figure 6(b) shows the dispersion diagram of one of the possible configurations calculated with the plane wave expansion method and based on the approximation of the slab-effective index. A silicon on insulator slab with height h of 260 nm was considered for this, with silicon and silica refractive indices of 3.48 and 1.44, respectively. The low index material is a top cladding layer of 1.6 refractive index filling holes and slit. A normalized hole radius of $0.3a$ was also considered to ensure a wide TE bandgap.

As seen in Fig. 6(b), a single-guided mode with a strictly monotonous slope was obtained for $l = 0.25a$, $dy = 0.4a$, $dx = 0.5a$, the band being tailored by adjusting the values of

$W2 (= 0.4\sqrt{3}a)$ and $W3 (= 0.5\sqrt{3}a)$ in order to flatten the sharply under the light line and to limit the expansion of the electric field within the lattice. Such a design also posses an inflection point just before the mode exits the light cone (i.e., near $k=0.4$). Therefore, it offers the possibility to slightly tune the band in order to have negative GVD. Here, we achieved an average group index of 140 over a bandwidth of 1.5 nm, associated with a very wide comb, i.e., 325 nm on average, which should considerably facilitate the filling of the slot by polymers or any other materials.

To express the confinement of the optical field, referring to the calculation reported in Ref. [38] can be done. In this publication, Almeida and co-workers defined the ratio η of optical power within the slot over the total power within a unit cell, and the optical intensity I as η divided by the cross-section of the slot, i.e., $W_s \cdot h$ with h the height of the slab. In case of standard slot waveguides, taken as a function of the slot width W_s , the ratio saturates around 30% for W_s higher than 200 nm, and I decreases from 30 to $3 \mu\text{m}^{-2}$ when W_s ranges from 10 to 200 nm. In that case, the confinement is done only by the index contrast and the group index remains around 3–4. In order to apply such factors in our case, we also needed to take into account the

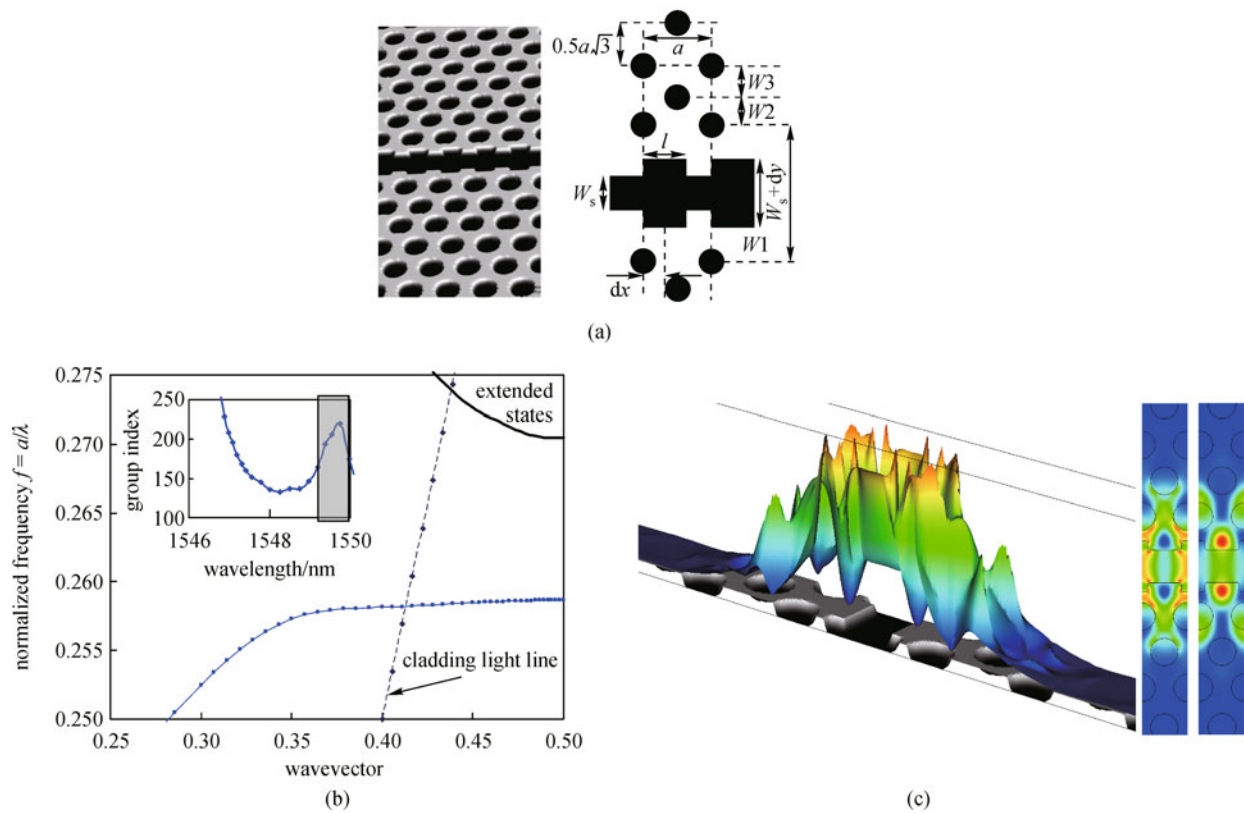


Fig. 6 Proposal for slot PhC waveguides relying on a Bragg-like corrugation of the slit and slow light propagation. (a) Schematic picture of the proposed waveguide geometry; (b) dispersion diagram for a silicon on insulator slab with height h of 260 nm, with silicon and silica refractive indices of 3.48 and 1.44, respectively, and $l = 0.25a$, $dy = 0.4a$, $dx = 0.5a$ (group index is plotted into the inset); (c) H_z component within space

increase of electromagnetic density due to the spatial compression of waves related to slow light propagation. Therefore, we expressed the optical density as the product of the group index and the previous optical intensity. In case of the new slot PhC waveguides we proposed, we found that the fraction of the optical power at $k=0.43$ within the comb is near 25%. Considering the group index around 140, an optical density as high as $540 \mu\text{m}^{-2}$ is thus obtained. This optical density represent an enhancement by a factor 7 if compared with typical values around $70 \mu\text{m}^{-2}$ just reported in previous works for classical TIR slot waveguides with narrow slots of 50 nm width, and a factor 40 if compared with more feasible slot width around 100 nm, whose optical density is around $12 \mu\text{m}^{-2}$. We believe that such waveguides combining a Bragg-like corrugated slit and slow wave phenomena can be used in future devices relying on non-linear optics or bio-sensors enhanced by large group light propagation.

6 Conclusion

Silicon photonics has raised a considerable interest in the last years. Many integrated optical passive and active functions have been demonstrated, including waveguiding, distribution of optical signals, optical modulation and detection, and wavelength demultiplexing. Applications of this research area now cover the fields of optical interconnects, high-speed receivers for optical networks, and bio-sensors. In many situations, enhancement of the light-matter interaction is perceived as an ideal route to shrink device dimensions and propose new optical functionalities. The exacerbation of nonlinear optical effects is a prime example, which can lead to the design of new features for all-optical processing of information. In this perspective, slow light propagation in photonic bandgap waveguide structures intrinsically fits with the objective of large optical densities. Overall optical propagation power indeed involves the product of group velocity and optical density. In this context, this article reviews the main current issues related to slow light photonic crystal waveguiding structures. The physical origin of slow light in periodical optical media is first reminded, putting the emphasis on the concept of dispersion diagram engineering to obtain nearly-constant group index in the largest possible bandwidth and controlling the GVD of involved waveguides. We also reviewed the last recent works related to the optical losses in slow light waveguides, involving both propagation and coupling loss issues and highlighting its importance for practical applications. For the same reason as the one responsible for enhancement of physical effects like optical gain or optical non-linear phenomena, optical losses are reinforced by the slow wave propagation due to increased field density available for field scattering over defects. Yet, we report recent results that showed that a proper design of

slow wave photonic crystal waveguides is possible to minimize this problem. As the whole, we conclude by an overview of recent applications of slow wave concepts to the design of integrated optical devices. Among them, small footprint optical devices, like modulators, have been already demonstrated. To conclude, future trends are given in the last part, focusing on the possible use of slow wave slot photonic crystal waveguides.

Owing to the recent progress of clean room technologies and to the accumulated knowledge about the physics of slow waves, issues like optical losses and limited bandwidth can be successfully managed. Although these drawbacks cannot be completely removed, the benefits coming from the field strengthening in slow light structures are extremely interesting for the design of future all-optical chips or ultra-sensitive optical sensors. For this reason, we strongly believe that slow light photonic bandgap structures can contribute to near-future breakthrough in silicon photonics.

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