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Slow-light: Fascinating physics or potential applications?

Slowing down the light for delay lines implementation: Design and performance

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Abstract

Optical delay lines are key building blocks for all-optical signal processing. Photonic crystal structures can demonstrate efficient group velocity reduction, together with a wide-bandwidth and reduced high-order group velocity dispersion. Theses structures also offer the ability for 2D integration within photonic integrated circuits. This paper presents the performances of photonic crystal structures engineered for slowing down the light, and discuss the actual limitation encountered due to fabrication imperfections. ***To cite this article: A. Talneau, C. R. Physique 10 (2009).***

Résumé

Lignes à retard tout optique : géométries spécifiques et performances obtenues à l'aide de structures à base de cristaux photoniques bidimensionnels. Les lignes à retard optiques sont un élément incontournable pour la mise en œuvre du traitement tout optique du signal. Les structures à base de cristaux photoniques bidimensionnels peuvent démontrer une très forte réduction de la vitesse de groupe, et ceci sur une large bande spectrale, tout en ayant des dispersions de la vitesse de groupe faibles. Ces structures sont aussi facilement intégrables dans les circuits intégrés photoniques planaires. Cet article présente quelques structures en cristaux photoniques dessinées de façon à supporter des modes optiques de faible vitesse de groupe, et il discute les limitations que les imperfections de fabrication entrainent sur les performances accessibles. ***Pour citer cet article : A. Talneau, C. R. Physique 10 (2009).***

Keywords: Photonic integrated circuits; All-optical signal processing; Delay lines; Photonic crystals; Slow light

Mots-clés : Circuits intégrés photoniques planaires ; Traitement tout optique du signal ; Lignes à retard ; Cristaux photoniques ; Lumière lente

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1. Introduction

All-optical signal processing is a key step for further integration of optical functions. Avoiding optical–electrical conversion is cost-saving and provides transparent bit-rate processing. Optical pulse storage or pulse reshaping could be performed provided we are able to control the optical mode's group velocity and its group velocity dispersion. A large bandwidth (∼10 nm) is of interest when going to 40 Gb/s bit rate or even higher. In the case of delay line

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implementations, low group velocity simultaneously with nearly zero first-order and second-order group velocity dispersion – GVD – is mandatory to avoid pulse distortion.

The group velocity v_g is the most meaningful parameter to characterize the slowing down of the light because it describes the speed at which a pulse envelope propagates. A reduced v_g is generically obtained as a consequence of a large phase index dispersion ($n_\phi = \omega/k$). Within a guiding structure, a large dispersion can be artificially produced in the material itself, or it can be obtained for the optical guided mode by a proper design of the guiding structure.

A strong *material dispersion* is exhibited in the case of Electromagnetic Induced Transparency (EIT). This mechanism is based on the coherent resonance of light with photo-excited atoms in a vapor gas usually at low temperature, and gives rise to a huge group index $n_g \sim 1000$, but on a very reduced bandwidth of tens of Hz, limited by the spectral linewidth of the excited level [1,2]. Coherent population oscillation, whereby a large modulation of carrier population eventually controls the fate of the wave, has also been demonstrated in solid materials, still on a much reduced bandwidth [3].

A large *structural dispersion* of the phase index is also achievable for the optical mode supported by a guiding structure. The group velocity reduction is less important in this case than in the case of EIT, $v_g \sim c/100$ but it is obtained on a larger wavelength span (∼0.1 to 10 nm) and can be more easily tailored according to the guiding structure design.

Microring coupled-resonators slow down the light because it takes a longer time to an optical signal to tunnel from one resonator to the next one, all along the resonator chain [4]. The group velocity can be reduced to $c/30$ but the bandwidth is still limited to 17 GHz due to the weak coupling between the resonators. However, resonators, as well as EIT, do not maintain the waveform shape of a short pulse due to the large group velocity dispersion (GVD) that exists close to these sharp resonances.

The periodic environment within *photonic crystals waveguides* (PhCWs) can be modified to tailor the shape of the $\omega(k)$ dispersion curve, thus providing reduced group velocity region and widely engineered GVD properties [5,6], on a large bandwidth (several nanometers). In the case of delay lines, engineered structures are investigated in order to produce the best trade-off between low group velocity and large bandwidth, for zero GVD. The delay-bandwith product should then be the most meaningful parameter for structures dedicated to optical signal processing [7]. Additionally, these structures should exhibit an efficient power budget as well as efficient coupling to external optical circuits. A specific design has to be implemented for, e.g., the taper in order to access the slow mode.

We will discuss in this article the performance achieved by different PhC engineered guiding structures, and we will point out the impact of the fabrication imperfections on the actual slow light structures performance.

2. PhCWs on membranes

PhCWs of concern consist of a line defect of missing air holes within a PhC lattice. When implemented on a *membrane suspended in air*, guided modes supported by some of these defects can be intrinsically lossless: in-plane losses are suppressed for modes propagating within the photonic gap, and out-of-plane losses through coupling to radiation modes can be avoided if the operation is performed below the air light-line, which can be designed with substantial freedom in the case of high index contrast structures.

High index materials of interest include silicon due to its transparency at telecom wavelength and its mature technology. On another hand, III–V materials like GaAs or InP have the advantage of active behavior, mainly for nonlinear optics application when quantum boxes are included in the membrane. The membrane should be thin enough to support a single in-plane even mode below the air light-line. The parity of the modes is defined by their in-plane symmetry with respect to the waveguide core. The PhC periodicity is related to the material index and the wavelength used: a typical value is $a = 450$ nm, with holes diameters in the range of 200–240 nm for an operation at 1.55 μm with an air filling factor $f = 30\%$. In-plane modes of even parity (TE-like) are preferred for more efficient in and out coupling. Due to the strong modal confinement, the mode size is reduced and a taper is needed for acceptable coupling [8,9].

Taking in consideration all these requirements, PhCWs on suspended membranes are good candidates for an efficient delay line.

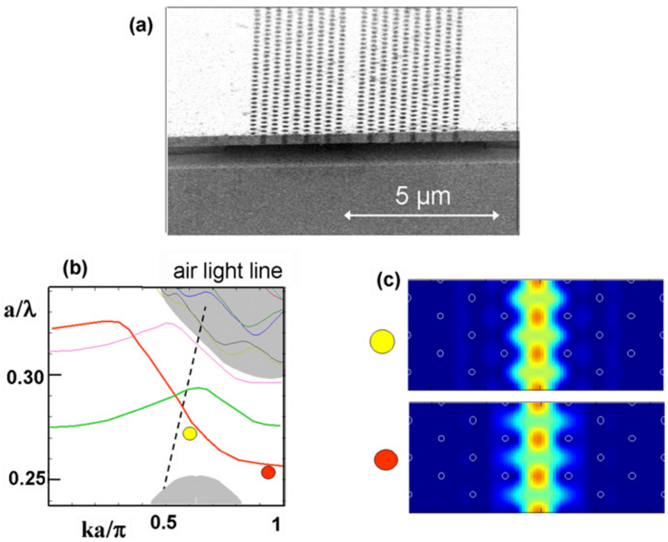

Fig. 1. (a) SEM picture of a W1 Photonic crystal waveguide on an InP suspended membrane. (b) Dispersion curve of a W1 PhCW for TE polarization, the membrane thickness is 260 nm and the air filling factor is 30%. (c) Longitudinal field pattern, for two values of the wave-vector k along the dispersion curve for the TE even fundamental mode.

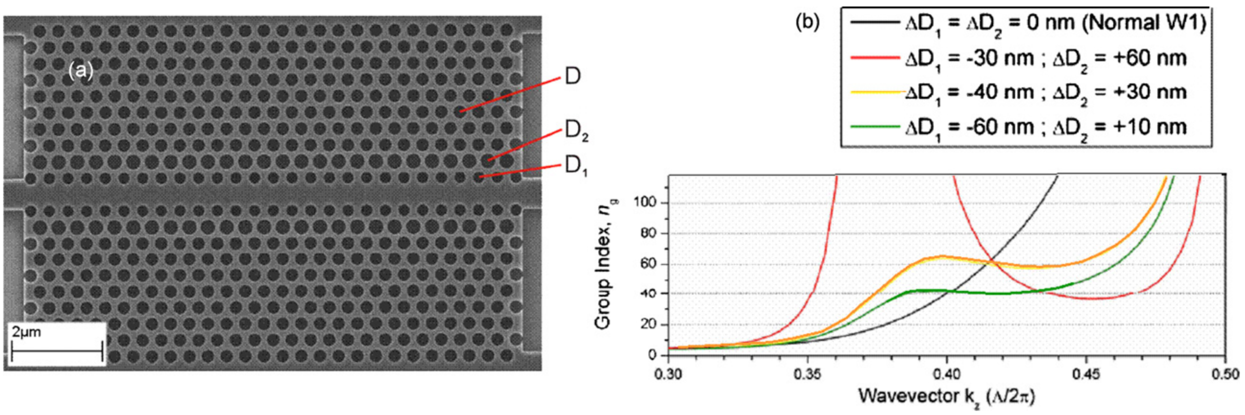

Fig. 2. (a) SEM top view of a transversally modified W1 PhCW and (b) calculated resulting group index according to the holes size variation [11].

3. Photonic crystal waveguides structures demonstrating slow light modes

3.1. W1 PhCW operating at the band edge demonstrates a large GVD

A conventional W1 PhCW is obtained by removing a single row of holes in the ΓK direction within a triangular array, see in Fig. 1-a a scanning electron microscope (SEM) picture of a W1 PhCW carved in an InP membrane. In this periodic structure, for TE-like polarization, the dispersion curve is folded in the first Brillouin zone. The even defect mode supported by the single missing row has its dispersion curve located inside the photonic gap of the PhC (red curve in Fig. 1-b), part of this curve being below the air light-line, thus corresponding to intrinsically lossless propagation. Close to the band edge, the dispersion of the dispersion curve (the group index) is increased to infinity leading to a formal value of zero for the group velocity. But such a band edge mode is not of interest since the GVD is concomitantly very large. Fig. 1-c plots the longitudinal mode profile (Hy component of the TE mode), evidencing the longitudinal distribution evolution when going from an “index guided” mode (yellow spot) to a low group velocity “gap guided” mode (red spot) at the band edge: the mode then spreads on the lateral rows, mainly the first two inner rows, and its resonant behavior is enhanced.

These mode plots could be a starting point for designing slow light structures. In order to obtain a zero GVD, which is mandatory for actual implementation, the dispersion curve of the gap guided mode has to be shaped as a straight line. We discuss the attainment of this ideal target in the following.

3.2. Structures based on the interaction of two modes within the same guide

Basically, the dispersion curve of the defect mode will be modified when the gap guided mode and the slab mode in the dielectric band (lower band) are moved close one to the other, and then forced to interact, giving rise to their anti-crossing. If this interaction is properly controlled, the dispersion curve of the gap guided mode can then be nearly shaped as a straight line.

We will present here two realizations of such a mechanism.

3.2.1. Reducing the PhW width

High-order dispersion management has been investigated by Petrov et al. [10] who proposed a modified W1 PhCW to produce vanishing second and third-order dispersion, together with a low group velocity. A line-defect waveguide is formed by leaving out a row of holes in the ΓK direction and shifting the boundaries together, the width is then defined by the percentage of $W = 3^{1/2}a$, a being the lattice period. Reducing the defect size from W1 to W0.7 and choosing the proper air filling factor produces an even gap-guided mode whose dispersion curve is quasi-flat, far from the band edge. Specifically, a quasi-constant group velocity of $0.02c$ is obtained on a large 1 THz bandwidth, with first and second order GVD being negligible. However, within such a reduced width waveguide, the mode is very strongly confined and access requires a specific taper design.

3.2.2. Changing the hole size on inner rows

Keeping the nominal W1 width and reducing the diameter of the innermost air holes on both sides of the single line defect has been proposed by Frandsen et al. [11] (Fig. 2-a). This design is reminiscent of that proposed in microstructured optical fibers, where three rows of holes where gradually increased to fit the hole size of the structure, leading to an ultra-flattened chromatic dispersion [12]. According to the diameter of these holes, the dispersion curve can be changed to a nearly straight segment, as can be seen in Fig. 2-b, leading to a group index n_g of 34 on a 11 nm wavelength span. The group velocity dispersion is not addressed here.

3.3. Coupled cavity waveguide CCW

3.3.1. Coupled cavity waveguide

Coupled cavity waveguides (CCW) in a PhC environment have been proposed by A. Yariv ten years ago [13] as a principle to guide the light by successive hopping from one cavity to the next. These guides can slow the light down simply because the light is stored in each cavity. The coupling strength between the cavities determines the spectral width of the resulting transmission windows. In the case of weakly coupled cavities, each cavity mode linewidth is small and the optical transmission is composed of well-separated sharp peaks. Such a transmission has to be avoided since an input pulse is transformed into its convolution by this frequency comb. Going to stronger coupling between the cavities leads to softer resonances, thus forming a transmission band. An input pulse can then propagate without distortion, provided that all its spectral components are included in the transmission band.

These coupled-cavity waveguides will suffer from intrinsic propagation losses due to the allowed coupling to radiation modes when folding the dispersion curve by the additional periodicity. These drawbacks have been investigated theoretically in [14], but the proposed conclusions are of limited impact since a detailed calculation taking into account only the components of the Bloch mode that are coupled to radiation modes was not performed.

3.3.2. Weakly-coupled cavity waveguides

CCWs can be obtained within a slightly modified nominal W1 waveguide where the lattice constant is periodically varying. Such a design has been proposed by Noda [15]: the cavities are formed by four successive periods of lattice constant $a = 430$ nm separated by barriers consisting of two periods of lattice constant $a = 420$ nm, thus creating a double heterostructure (Fig. 3-a). The group index has been measured by the Fourier space imaging technique [16]. Analyzing the intrinsic out-of-plane losses of the CCW gives access experimentally to the dispersion curve. A group

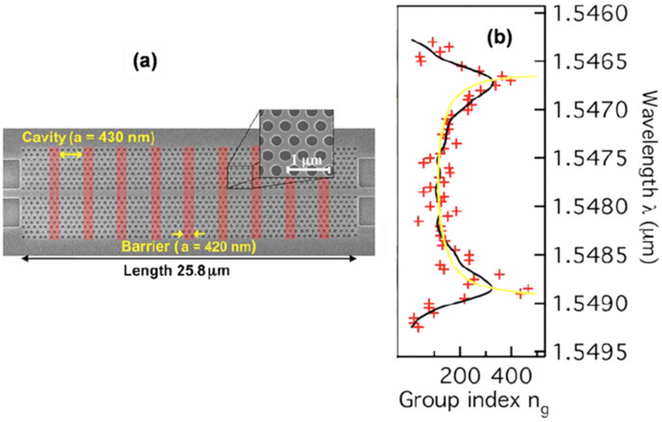

Fig. 3. (a) Coupled resonator optical waveguide – CROW – based on cavities formed by four successive periods of lattice constant $a = 430$ nm separated by barriers consisting of two periods of lattice constant $a = 420$ nm. (b) Measured group index on such a structure by Fourier space imaging [17].

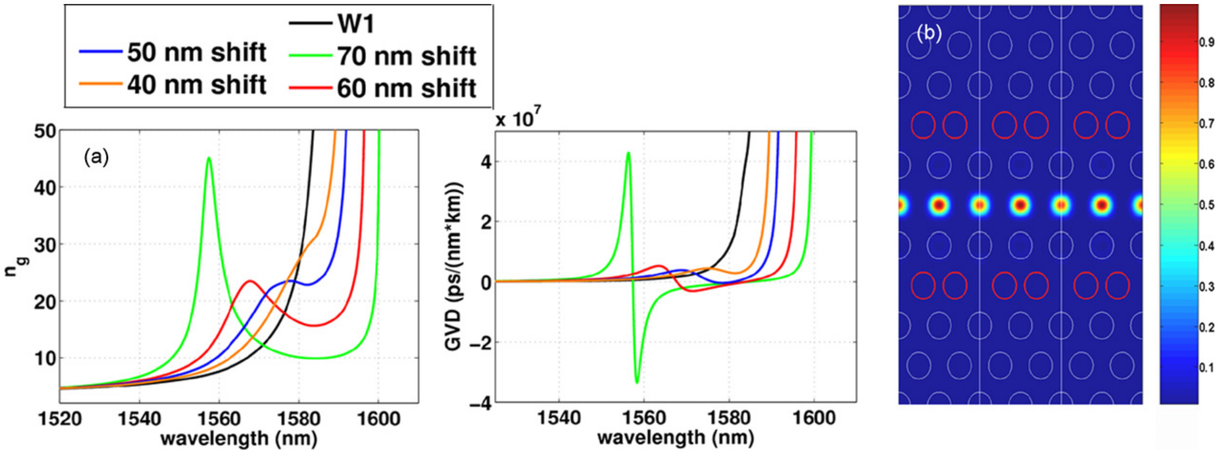

Fig. 4. (a) Group index and GVD for a strongly coupled cavity W1 PhCW, with shifted holes on the second row. (b) Modal field distribution in the modified (50 nm-shifted holes) W1 [19].

index as high as $n_g \approx 105$ is measured on a 2.6 nm span (Fig. 3-b) [17]. Due to the added periodicity, the Brillouin zone is reduced, leading to locate some of the components of the Bloch mode above the air light-line, and thus producing intrinsic out-of-plane losses. These losses could be limited according to the Bloch mode components involved, and they can even be here judiciously used for imaging purpose [16–18].

3.3.3. Strongly coupled cavity waveguides

Going to stronger coupling between cavities will reduce the achievable group index but as a consequence will lead to an increased wavelength span. Looking at the plot of the longitudinal mode distribution (Fig. 1-c) suggests that a nominal W1 waveguide, when approaching the cut-off, can be viewed as a CCW. Based on this observation, we consider to shift holes on the second row and along the direction of propagation with a period $2a$ (a being the PhC period). This gives rise to strongly coupled cavities, and in this structure a nearly constant semi-slow light behavior $n_g = 24$ over a 12 nm wavelength range is obtained, with an almost zero GVD (Fig. 4-a). The coupled-cavities enhancement of the modal field distribution is clearly visible Fig. 4-b [19].

3.4. Coupled PhCW

A dispersion curve including an inflexion point for the even guided mode can be produced in a structure where two adjacent PhC guides are coupled by the intermediate of some rows of holes [20]. The even super-mode supported by

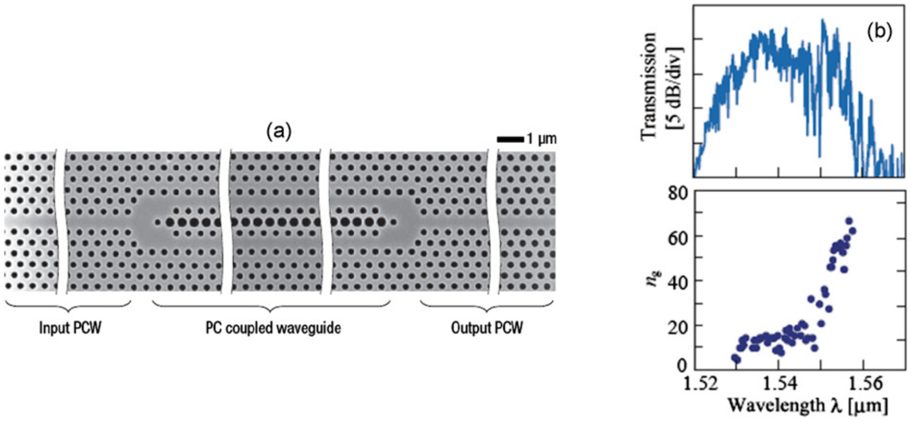

Fig. 5. Coupled waveguides for versatile and large wavelength domain of low v_g and zero GVDs. Tapered access to the slow light mode is also included. (a) SEM picture. (b) Measured transmission and group index [20].

these two coupled PhCW can exhibit zero v_g and zero GVD at the inflexion point. By employing a chirped structure having gradually varying parameters, the inflexion point is shifted over a bandwidth determined by the range of the chirp. Consequently, the slow light is obtained in the whole bandwidth and the GVD is compensated within the bandwidth. This design presented in Fig. 5-a provides a large group index of $n_g = 60$ on a 10 nm span (Fig. 5-b), with the advantage of a very large design flexibility to adjust the desired wavelength span, but at the expense of a more sophisticated design. In particular, its operation relies upon the perfect 50% division of the guided mode in both branches.

3.5. Design conclusions

Several PhCW designs produce slow light modes with reduced GVD. A coupling mechanism is involved to shape the dispersion curve as a straight line. Including a tapering section for efficient access to the low group velocity mode is additionally required for a large power budget.

All these designs include a finely-adjusted modification of the size or position of the holes in the lattice. These guiding structures have a large spatial extent, and they rely upon a resonant behavior. All the irregularities on the periodic lattice will then translate into an additional phase, thus affecting the guided mode and as a consequence the structure performance. The impact of fabrication imperfections is now investigated.

4. How slow can we go?

Photonic crystal waveguides on suspended membranes are of interest because optical modes with tailored dispersion properties can propagate, in theory, without losses. However, unavoidable structural fabrication imperfections break the PhC periodicity and the prominent idea is that this modestly broken periodicity is enough to destroy the Bloch wave coherence. Imperfections originate from etched surface roughness, and dispersion on holes size, shape and position; at first order disorder does not destroy the vertical symmetry, thus polarization mixing is prevented. Dispersion on the geometrical dimensions originate from pattern definition, either produced by direct electron-beam writing, or by nanoimprint lithography whereby a mold is required [21].

Several attempts have been undertaken to understand how fabrication imperfections impact the achievable reduced group velocity.

Scattering into the backward propagation mode [22,23] has been proposed as a dominant mechanism, responsible for increasing losses and for limiting the desired group velocity reduction. Theoretical investigations describe interferences of coherently back scattered waves resulting in the formation of narrow band, thus supporting propagation of light, but these bands are spectrally narrow and will not allow the correct undistorted transmission of an optical pulse.

An experimental investigation also has to be performed.

Scanning near-field optical microscope (SNOM) is an efficient experimental tool for tracking the modal behavior of an optical structure. Measurements from a chirped W1 waveguide on Si membrane reveal that losses scale proportionally to v_g^{-2} for group velocities above $\sim c/30$, while below $c/30$ the modal pattern becomes irregular, indicating multiple scattering [24]. The slow light behavior is here limited by scattering to $v_g = c/30$.

The behavior of slow light modes can also be tracked by experimentally reconstructing the dispersion curve in k-space. Due to disorder, Le Thomas et al. proposed that the coherent regime is lost and a diffusive regime takes place, where multiple scattering occurs [18]. Within the coherent regime, the group velocity is a correct parameter describing light propagation, while this parameter looses its relevance in the diffusive regime where the *energy transport velocity* should then be considered instead.

When comparing the different structures providing slow light modes, the wavenumber at which the reduced group velocity operates has to be considered. The frequency power spectrum associated with residual lattice disorder has been experimentally measured to be centered around wave vectors equal to the PhC reciprocal wavevectors [18]: as a consequence, structures operating close to a band edge will be more affected than PhC CCW. The group velocity could not be measured lower than $c/30 \sim c/50$ for guiding structures, but $c/150 \sim c/200$ has been measured for PhC CCW [17].

5. Conclusion: what could be expected, what has to be done?

Technological optimization of fabrication processes is under progress in order to reduce the typical dimensions of static disorder. While roughness of etched surfaces has been greatly optimized, disorder on the lattice produced during electron beam lithography (EBL) patterning is still under consideration. The latest EBL tools are now able to produce patterns with a writing accuracy below the nm range. In order to obtain a fixed delay, short structures will be preferred such as CCW which are able to demonstrate $n_g = 100$ on a 25.8-μm-long structure [17]. At the same time new structure designs, expected to be less sensitive to disorder, should be investigated. The concept of disorder immune designs has already been proposed for resonant structures [25] where the modal extension is limited to the cavity. This concept could be investigated for guiding structures.

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