Low Dispersion Slow Light in Silicon-on-Insulator Photonic Crystal Waveguide

[a]Amir Hosseini, [a]David Kwong, [b]Harish Subbaraman, and [a]Ray T. Chen
[a]Department of Electrical and Computer Engineering, University of Texas, Austin, TX 78758, USA
[b]Omega Optics, Inc., 10306 Sausalito Dr, Austin, Texas 78758, USA
(e-mail: ahoss@mail.utexas.edu; chen@ece.utexas.edu)

ABSTRACT

We present a design methodology for silicon-on-insulator photonic crystal waveguides to achieve wideband low-dispersion slow light with only tuning the position of the first three inner rows. We aim to maximize the group index – bandwidth product or the slowdown factor. Our design achieves a constant group index of 39.3 over 12 nm bandwidth around 1550 nm, corresponding to a slow down factor of 0.3.

Keywords: Photonic crystal waveguide, silicon photonics, slow group velocity, group velocity dispersion.

1. INTRODUCTION

The interest in manipulating the speed of propagating light has increased dramatically in recent years for applications such as optical delay lines [1], optical buffers [2-3], and all-optical switches [4-5]. The possibility to compress the energy and signal provides the opportunity for reducing the footprint of the devices. In addition, the strong light-matter interaction due to the small group velocity enhances absorption, non-linearity, and gain per unit length which benefits numerous optical devices such as detectors, amplifiers, and lasers [6-7]. In recent years, the engineered slow light photonic crystals have drawn a great deal of attention by researchers because of the flexibility in design and compatibility for on-chip applications.

Three dimensional semiconductor photonic crystals (PC) with a complete band gap are ideal candidates for these applications, but their fabrication is challenging. Planar photonic crystal slabs fabricated on semiconductor membranes, such as silicon on insulator (SOI) wafers, where light is confined in-plane by the two-dimensional (2-D) photonic crystal and vertically by total internal reflection of index contrast, are an alternative solution because of their relative ease of fabrication [8-10].

However, the narrow bandwidth due to the highly dispersive group velocity of the photonic crystal slabs in the slow light regime restricts their applications [11]. Several research groups have achieved low group velocity dispersion by adjusting the waveguide width [12-14], the size of the first two innermost rows of holes [15-16], the displacement of the first two innermost rows [17], shifting the third innermost rows along the waveguide [18], chirping the property of photonic crystals, such as the radius of the air holes or the periodicity [19], or by adjusting the parameters of capsule shaped holes on silicon nanomembranes [20].

Most of the abovementioned techniques were implemented on air-bridged structures [17-20]. The largest slowdown factor (SF), normalized bandwidth – group index product, reported so far for a silicon-on-insulator photonic crystal structure (with silica as the lower cladding layer) is 0.24 [15],

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which is realized by perturbing the holes adjacent to the waveguide core. Since the useful bandwidth lies below the silica light-line in such a silicon-on-insulator (SOI) photonic crystal, tailoring the band structure for constant group velocity propagation over a wide bandwidth is challenging. It is also more difficult to linearize the band structure closer to band edge, where the group velocity dispersion diverges.

A design with different air hole sizes requires precise control of multiple parameters, which must be simultaneously adjusted by several rounds of calibration and measurements [18]. In this paper, we present a design methodology for maximizing the slowdown factor by changing the positions of the first two innermost holes and width of the line defect photonic crystal waveguide (PCW), and by shifting the third rows of air holes parallel to the line defect. We show that the presented scheme renders itself for low and high group velocity sections [21-23] for coupling to input/output dielectric waveguide improvement.

2. DESIGN OF THE PHOTONIC CRYSTAL WAVEGUIDE

A SOI photonic crystal slab waveguide with a hexagonal lattice of circular air holes is shown in Figure 1(a). The refractive index of the silicon slab, n, is 3.47 at λ=1.55 µm and t (thickness of slab) is 0.6a, where a is the lattice constant. The lower cladding is SiO_2 (n_{SiO2} =1.45), and the top cladding is air. The slab is laid on the x-z plane and a line waveguide is formed by removing a single row of holes along x direction in real space which corresponds to the ΓK direction of the reciprocal lattice. Due to the introduction of the line defect, the Brillouin Zone edge is shifted from K to K' instead. The band structure of the photonic crystal, as illustrated in Figure 1 (b), is calculated using BandSOLVE^{TM} of the Rsoft Photonics CAD Design Suite based on three dimensional plane-wave-expansion (PWE) method and projected from the ΓM direction onto the ΓK' direction, which gives

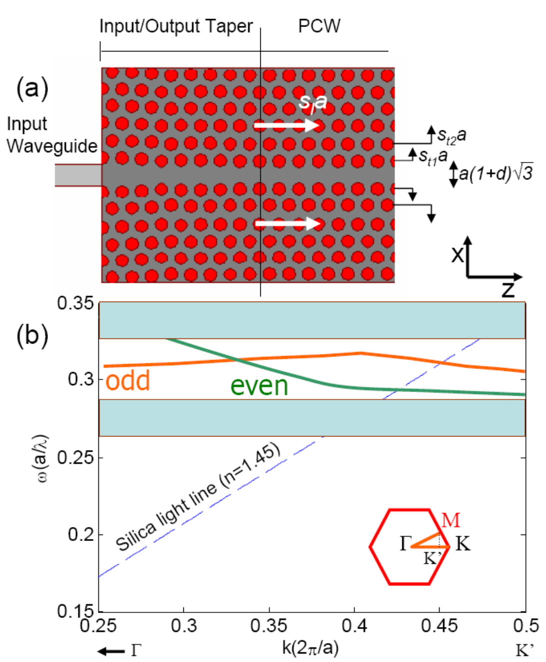

Figure 1 (a) A schematic of the band-engineered PCW structure and the input/output coupling taper structure. The design parameters (s_{t1}, s_{t2}, s_l and d) are shown. The input and output tapered PCW couplers are mirror images of each other in the actual implementation. (b) A typical band diagram of the SOI photonic crystal waveguide. The useful part of the band lies below the silica line.

the boundary of the first Brillouin zone. The defect modes inside the band gap are studied by replacing a 1 × 1 × 1 unit cell with a supercell which is 10 units in the x direction, 1 units in the *z* direction, and 4 units in the y direction in the PWE calculations. The figure also shows a lateral even guided mode and a lateral odd guided mode, and both of them are vertical even modes. The vertical even mode is defined as the mode symmetric with respect to the *x-z* plane. The lateral even guided mode is defined as the mode symmetric with respect to the *x-y* plane, which is a fundamental mode, while the lateral odd guided mode is a higher order mode.

The group velocity of a guided mode is calculated from its definition as the derivative of the angular frequency with respect to the wavevector.

$$v_g \equiv \frac{\partial \omega}{\partial k} \tag{1}$$

The derivative of the reciprocal group velocity with respect to the frequency gives the group velocity dispersion (GVD), as follows

$$GVD = \frac{\partial (1/v_g)}{\partial \omega}. \tag{2}$$

In photonic crystal slab waveguide modes, there coexists gap guided modes and index guided modes. A high GVD happens at the anticrossing point where gap guided modes and index guided modes couple with each other [11]. One can tailor the dispersion curve and shift the anticrossing point by engineering the parameters of the line defect. Frandsen et al. have proposed an approach to "flatten" the dispersion curve by perturbing the size of the periodic holes of the two innermost rows [15]. An alternative approach that this paper presents, aims to control the shift of gap guided mode, thus flattening the dispersion curve via 1) manipulating the width of the defect line, which is originally $a\sqrt{3}$ (for d=0), 2) by shifting the positions of the first two inner rows in the transverse direction (s_{t1}, s_{t2}), and 3) by shifting the third row parallel to the PCW (s_l). The radius for all the air holes is the same, $r \times a$. We assume a=400 nm.

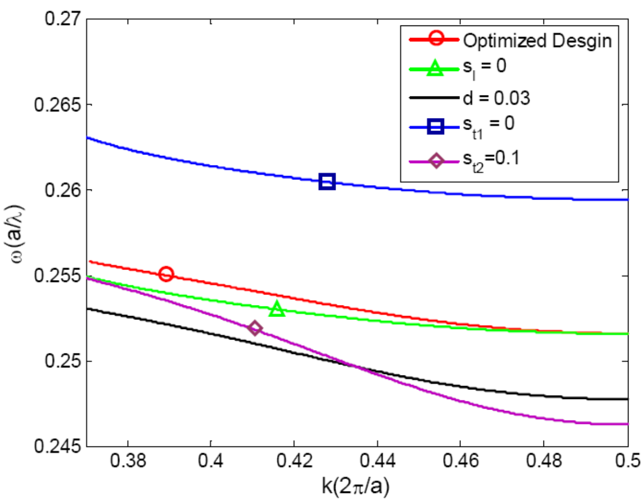

Figure 2 Band diagram for the optimized design, s_{t1}=0.1, s_{t2}=-0.02, s_l=0.18, d=-0.043 and r=0.29 is shown by the red solid (circled) curve The other curves correspond to the band structures for change in one design parameter with the remaining being the same as the optimized design as indicated in the graph legend.

The effect of the changing each parameter is depicted in Figure 2. Reducing s_{t1} shifts the whole band to higher frequencies, which is similar to increasing air hole radius. Increasing s_{t2} shifts the band at the Brillouin Zone edge downward as discussed in [17]. Increasing s_l shifts the low k part of the band upward. Increasing d shifts the whole band downward and reduces the group velocity as the high K part of the band moves more rapidly toward lower frequencies.

We notice that if the useable part of the band, which is below the silica light line, is linearized, the group index ($n_g=c/v_g$) and the normalized bandwidth are given as $\Delta k/\Delta\omega_n$ and $\Delta\omega_n/\omega_{n0}$, respectively, where ω_n and ω_{n0} are the normalized frequencies given in a/λ. Δk and $\Delta\omega_n$ correspond to the part of the guided mode band below the silica line. Therefore, SF is approximately $\Delta k/\omega_{n0}$. In order to increase the slowdown factor, we need to increase the useable part of the band in order to enhance the slowdown factor. However, we find that pushing the band structure downward also lowers the group index. A combination of the abovementioned design parameters enables enhancing the slowdown factor for large group index values (n_g>30).

3. DESIGN OPTIMIZATION RESULTS

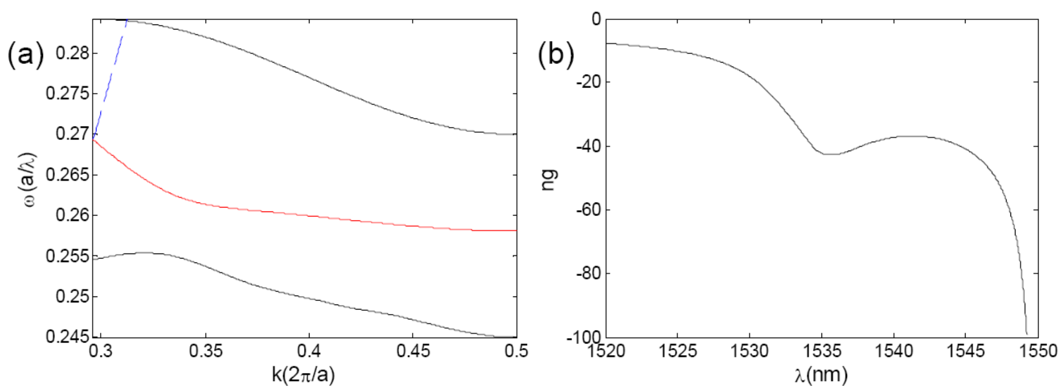

Figure 3 Optimized design results (s_{t1}=0.1, s_{t2}=-0.02, s_l=0.18, d=-0.043 and r=0.29), (a) band diagram (b) group index versus input free-space wavelength for a=400nm.

In order to accurately and efficiently solve the optimization problem for maximum SF while keeping large group index values, the appropriate optimization techniques must be utilized. When considering a single degree of freedom in the design problem, the typical approach has been to enumerate over the range of possible cases in order to locate a design that provides low loss while meeting constraints on light confinement, loss, and waveguide geometry [24]. However, for the simultaneous design of s_{t1}, s_{t2}, s_l, d and r, enumeration provides an inefficient means to locate the optimal geometry.

Since the design problems are nonlinearly constrained optimization problems, we utilize sequential quadratic programming (SQP), a nonlinear programming technique that exploits the gradients of the objective and constraint functions at each iteration to accelerate convergence [24]. The SQP and other gradient-based optimization routines require both objective and constraint functions to be convex to guarantee that the algorithm will produce the global minimum for the optimization problem. A function is convex if its Hessian is positive semidefinite for all possible design variable

values. If the design space is not convex, the SQP will only converge to a global minimum if the algorithm's start point lies in the convex set containing the global minimum [24].
The optimum design parameters are found to be s_{t1}=0.1, s_{t2}=-0.02, s_l=0.18, d=-0.043 and r=0.29. Figure 3 (a) shows the band diagram of the optimized design. The variations of the group index versus the input wavelength are shown in Figure 3 (b). The frequency interval over which group index fluctuations remain within ±10% is considered the bandwidth. Figure 3 (b) demonstrates an n_g=39.3 over 12 nm bandwidth corresponding to SF=0.3, which shows 20% more than the previously reported slowdown factor for a silicon-on-insulator PCW [15].
Compared to air-bridged structures, the SOI structure is more mechanically stable, especially for long PCW devices. It is also more suitable for 3D stacking or polymer or glass refilled PCs [25-26]. Our optimized design is able to provide low-dispersion slow light propagation with a slowdown factor similar to the values reported for air-bridged structures [15-20].

4. TAPERED PHOTONIC CRYSTAL WAVEGUIDE FOR EFFICIENT COUPLING

In order to prevent high total losses, in addition to minimizing the fabrication errors, we also need to make sure that the light coupling from the input waveguide to the photonic crystal is efficient at high n_g values. As shown in [27], direct butt-coupling between PCW and conventional dielectric waveguide is prohibitively inefficient at high n_g, because the butt coupling efficiency is given as

$$\eta = \frac{4 n_{g,PCW} n_{g,DW}}{(n_{g,PCW} + n_{g,DW})^2} \quad (3)$$

where $n_{g,PCW}$ and $n_{g,DW}$ are the group indices of the PCW and the dielectric waveguide, respectively. In order to ensure highly efficient coupling, it has been proposed to adiabatically change the group index using tapered PCWs in the input and output of the high index PCW region [21-23].
Figure 4 shows the band structures and n_g versus wavelength for 3 low dispersion (flat band) designs with lower group index values suitable for being used in the taper structures shown in Figure 1. It is important to make sure that all the low group index bands cover the entire high group index bandwidth of the optimized design.

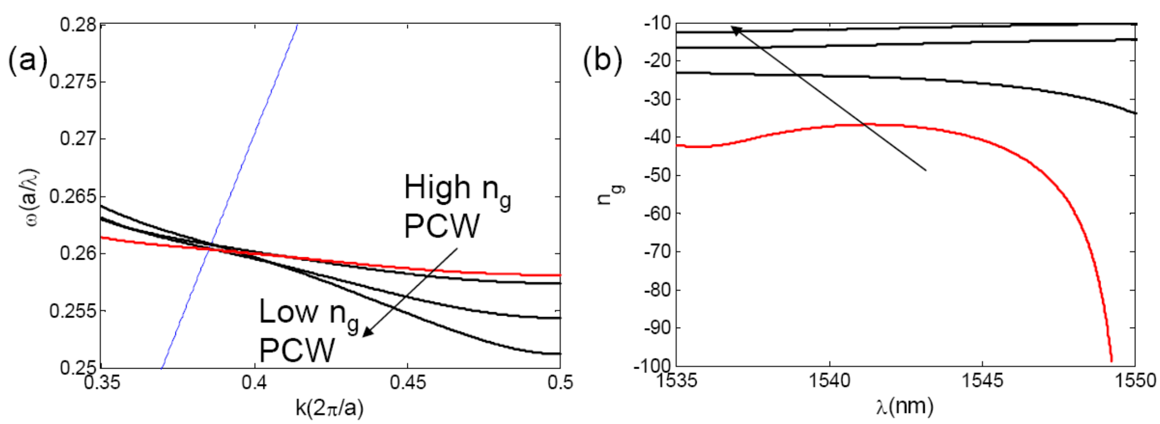

Figure 4 Taper structure results (a) band diagram, (b) group index versus wavelength for a=400nm. The red curve is the high group index (optimized design). The four curves in (a) and (b) from high to low group index correspond to (s_{t1}=0.1,

s_{t2}=-0.02, s_l=0.18, d=-0.043 and r=0.29), (s_{t1}=0.05, s_{t2}=0.06, s_l=0.18, d=-0.037 and r=0.29), (s_{t1}=-0.02, s_{t2}=0.115, s_l=0.18, d=0.03 and r=0.29) and (s_{t1}=-0.14, s_{t2}=0.15, s_l=0.18, d=0.14 and r=0.29), respectively.

5. CONCLUSIONS

We present a design methodology for low-dispersion slow light photonic silicon-on-insulator crystal waveguides with enhanced slowdown factor. Utilizing the usable part of the band structure under the silica light line, we demonstrate a slow down factor of 0.3 with group index near 40. By linearizing the band structure while shifting the position of the low and high k parts of the band, we designed tapered photonic crystal input/output couplers. The results will be used for the design of PCW structures with bottom and/or top silica claddings.

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