On the Design of Highly Dispersive Photonic Crystal Waveguides for Optical Delay Lines

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Abstract— **We present a design methodology for optimized highly dispersive photonic crystal waveguide delay lines. The results indicate that higher group-indices lower the total propagation loss as long as perturbative backscattering is the dominant loss mechanism.**

Planar photonic crystal waveguides (PCW) fabricated on semiconductor membrane, such as silicon on insulator (SOI) wafers have been considered for slow-light applications, such as optical buffers, optical delay lines and optical switches [1], [2]. There two main categories for slow light PCWs, low dispersion (flat band) low-group velocity PCW, and highly dispersive PCW. The former can be represented simply as a waveguide with a high refractive index, whish in turn results in a high group index (n_g>20). The flat band low dispersion band would allow large bandwidth pulses to propagate without pulse shape distortion [4], [5]. If one wishes to use a low dispersion PCW in a system which requires control over the delay time, one would need to have several lines of different group indices and optical switches to direct the input light selectively to a line with the desired delay. However, in case of applications, such as optical phased arrays, where the several channels with tunable delay times are needed, the cost and complexity of such a scheme is prohibitive. Despite of being narrow bandwidth, the later provides much better tunability over the delay by simply tuning the input light wavelength within less than 10nm bandwidth. In this paper we aim at an optimum design based on highly dispersive PCWs for optical delay lines.

The operation principles are similar to those of the highly dispersive photonic crystal fibers [5]. The group velocity of a guided mode is calculated as the derivative of the angular frequency over the wavevector.

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

Group index is $n_g=c/v_g$, where c is the speed of light. The derivative of the reciprocal group velocity over the frequency gives the group velocity dispersion, *GVD*, as follows

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

Thus, if the input light wavelength is changed from λ_0 to λ_1, the change in the traveling time is given as

$$\Delta t = L\int_{\lambda_0}^{\lambda_1} GVD(\lambda)\cdot d\lambda, \tag{3}$$

where, L is the length of PCW. An important task is to determine the maximum delay time achievable for given length and propagation loss. The dependence of the propagation loss on the group index has been theoretically and experimentally investigated and it was shown that propagation loss is proportional to the square of the group index for small group indices [6], [7]. Experimental studies have shown that for group indices larger than about 30, the propagation loss can be excessively high [6]. In general, how large the group index can become before such phenomenon happen depends on the fabrication process, e.g. the surface roughness of the holes/rods. Recent theoretical studies investigated the crossover from normal light propagation into a disordered regime that is dominated by coherent scattering and concluded that while the propagation is highly disordered, strong localization is not happening. One of the thus far lowest propagation loss in PCWs was reported in [8] as 4.1±0.9 dB/cm at n_g=6. We will use this data and scale the loss by n_g^2 to estimate the achievable propagation loss for n_g values in the optimization process assuming propagation below the highly disordered regime.

Based on (3), high *GVD* values are needed for large delay times, that means the PC band (ω versus k) should be away from being flat. At the same time, we note that delay time depends on the *GVD* values not the n_g, and since propagation loss increases with n_g, it is important to engineer the photonic band to have largest *GVD* values at the lowest possible n_g values. One appropriate figure of merit for design optimization is the inverse of the total propagation loss (length × per-unit-length loss) for a give required delay time (here we choose Δt=1ns).

A PCW structure with input and output waveguide is shown in Fig. 1. A PCW is usually realized by removing one row of the holes. In our case, the photonic crystal is a hexagonal lattice, air holes (red) in silicon slab (gray). PCWs' properties are very sensitive to the radius (R) of the air holes and fabrication

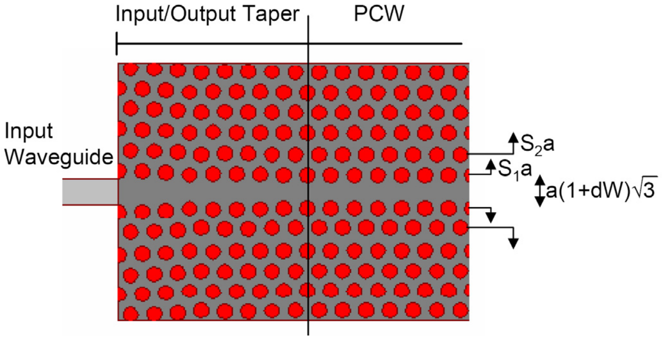

Fig.1. A schematic of the band-engineered PCW structure and the input/output coupling taper structure. The design parameters (S_1, S_2 and dW) are shown. The input and output tapered PCW couplers are mirror images of each other in the actual implementation.

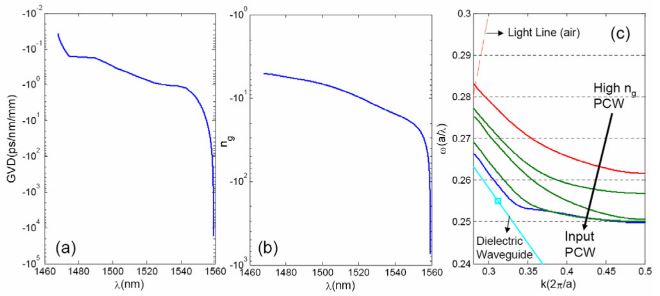

Fig.2. Variations of the (a) *GVD* and (b) n_g values with the input wavelength for R=0.28a, S_1=-0.1, S_2=+0.1, and dW=0. Changes in the guided mode band from the high group index PCW (R=0.28a, S_1=-0.1, S_2=+0.1, dW=0) to the low group index PCW (R=0.28a, S_1=-0.1, S_2=-0.1, dW=0.12) at the dielectric waveguide interface.

calibration process is very challenging for more that one precise feature sizes. Therefore, we have targeted at designs with the same radius for air holes. In order to engineer the band structure of the PCW, we tune 4 parameters. We tune the size of the gap (g) between the two innermost rows, which without any change is $a\sqrt{3}$, where a is the lattice constant. For a tuned structure g given as $(1+dW)a\sqrt{3}$. On top of this, we tune the positions of the two inner rows with respect to the tuned gap size, S_1 and S_2 as shown in Fig. 1. Note that the structure holds its inversion symmetry with respect to the PCW gap. By changing dW, S_1, S_2 and R, we optimize the band structure for highly dispersive applications by minimizing the total propagation loss.

We use BandSolve^{TM} to simulate the PCWs. It can be seen in equation (3) that the main contribution to the delay time comes form high *GVD* part of the mode band. In order to compare different PCWs in terms of the delay time, in all cases we set λ_0 to be where *GVD*=10ps/nm/mm. In the optimization process we have set λ_1 to be where n_g reaches 40. The band structure of the guided mode of the optimized PCW is shown in the inset of Fig. 2(c). For this device, R=0.28a. S_1=-0.1, S_2=+0.1, and dW=0. The variations of n_g and *GVD* with wavelength for a=408nm is shown in Fig. 2(a) and 2(b), respectively. It can be seen in Fig. 2(a) that *GVD*=10ps/nm/mm happens at λ=1550.53nm.

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 [9], direct butt-coupling between PCW and conventional dielectric waveguide is prohibitively inefficient at high n_g, because the butt coupling efficiency is given as

$$\eta = 4n_{g,PCW}n_{g,DW}/(n_{g,PCW}+n_{g,DW})^2 \qquad (4)$$

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 [10]. The PCW structure shown in Fig. 1 easily renders itself for implementation of group-index input/output tapers. We deigned an efficient taper structure for the 3D geometry by gradually reducing the high index of PCW band to a value which is close to that of the input/output dielectric waveguide, as shown in Fig. 2(c). The changes in the parameters S_1, S_2 and dW from the PCW toward the dielectric waveguide is geometrical to ensure a smooth group index transition.

The maximum achievable delay time per unit length ($\Delta t/L$) depends on the maximum achievable group index, max($|n_g|$), as shown in Table I. If the disorder induced scattering is small enough to allow max($|n_g|$)=60, the value of $\Delta t/L$ increases more than 100% compared to the case when max($|n_g|$)=40. Also, Taper I demonstrates that at high n_g values, although the loss/length is higher, the contribution of the high GVD in the integral in Equation (3) is so high that much shorter lengths are required and consequently, the total loss is less.

In summary, we optimized a highly dispersive PCW for delay line applications tunable by the input wavelength. We introduced design parameters in the PCW that enable band engineering for both highly dispersive PCW and input/output adiabatic reduction of the group index. We showed that the maximum achievable delay time per PCW length is limited by the maximum achievable group index propagation. This scheme also provides a means to determine the maximum supported n_g before the crossover into the highly disordered propagation happens by measuring the delay time. Our experimental group index measurement results will be published separately.

Table I

Max. $\lvert n_g \rvert$	λ_2 (nm)	Δt/L (ps/mm)	Loss (dB/cm)	L (mm) For Δt =1ns	Total propagation loss (dB)
40	1557.26	63.5	21.4	15.75	33.8
60	1558.36	130.1	25.0	7.69	19.2
80	1558.72	196.9	27.5	5.08	14.0
100	1558.90	263.4	29.4	3.80	11.2
150	1559.05	429.9	33.0	4.00	13.2
200	1559.11	595.7	35.5	1.68	6.0
400	1559.17	1265.2	41.5	0.79	3.3

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