

Increased Buffering Capacity over Ultra Large Bandwidth in Slow Light based Photonic Crystal Waveguides with Elliptical Nano-pillars



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Abstract

Propagation of slow light in a 2-dimensional, single line defect photonic crystal waveguide is investigated. Defects are formed by replacing circular dielectric pillar with elliptical pillars. A crystal is arranged with square lattice geometry. Slow light performance of the structure is tailored by controlling a single parameter i.e. an axial ratio of elliptical pillars but keeping its filling factor constant. We, aim to increase the figure of merit quantified by delay bandwidth product. The increased value of normal delay bandwidth product (NDBP= 0.3441) over the large bandwidth ($\Delta\omega= 12.4$ THz) is reported.

Keywords: Photonic crystal waveguide; Slow light; Aspect ratio; Normalized delay bandwidth product

Introduction

In recent years slow light has attracted a strong interest because of its unique feature to be realized as future on-chip optical networks based buffers [1] and switching [2]. Besides of optical buffers, light with reduced group velocity is used to enhance the weak light-matter interaction by spatial compressing the optical pulse and increasing the peak intensity [3,4]. Slow light effects can be exploited using variety of techniques, including electromagnetically induced transparency (EIT) [5] mediums, coherent population oscillation [6], and optical coupled resonators or photonic crystal waveguides (PCW) [7]. Photonic crystal waveguide (PCW) provides an efficient means to generate slow light at room temperature and dispersion free propagation over the largest possible bandwidth. The periodic modulation of refractive index greatly affects the optical dispersion relation. Photonic crystal exhibits a range of optical frequencies that are forbidden to escape, called photonic band gap. Optical frequency lying within the band gap can be guided efficiently by omitting one or more rows of holes/ rods pillars from the perfect crystal.

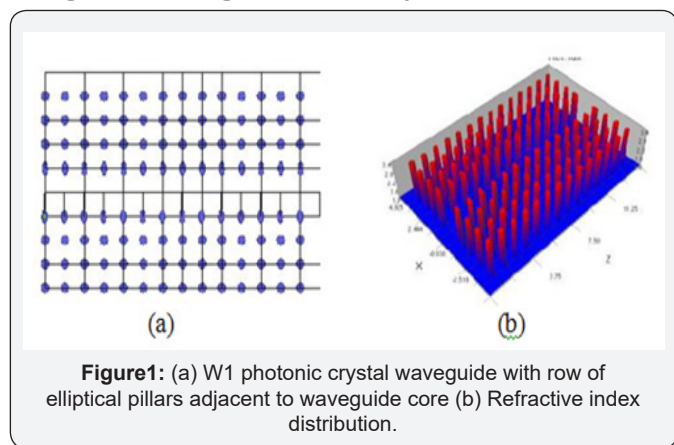
The structure with missing row of dielectric pillars/ holes is called photonic crystal waveguide [7,8]. These waveguides sustain guided modes in the photonic band gap region and has strong anti-crossing effect at the band edge [9]. An interesting feature of PCW's is that light will propagate with reduced velocity

near band edge for specific frequency [10]. W1 photonic crystal waveguide (PCW) is generally used for slow light generation because it avoids coupling between adjacent modes. Frequencies of guided modes vary parabolically with the wave vectors. The same effect is quantified by group velocity dispersion (GVD) that leads to temporal broadening of optical pulse. Thus, the obtained bandwidth gets limited due to slow light transmission. Different authors have presented different techniques to reduce the distortion caused by GVD effect by chirping methods [11,12] or by modifying the structural parameters from the standard W1 waveguide [13-15]. Chirped devices are not suitable for the enhancement of light-matter interaction because the group velocity of optical signals in the chirped waveguide does not remain low all along the waveguide.

Several researchers have achieved low group velocity by modification of parameters such as radius of pillars [14], period [15] etc. In the modified structure there is an intrinsic interaction between gap guided and index guided modes that lead to an anti-crossing effect. In contrast to chirping methods, structural modifications enhance all the nonlinear optical effects. In this paper, we explore a simple method to generate slow light in the largest possible bandwidth by replacing the row of circular dielectric pillars adjacent to waveguide with the row of elliptical pillars. Numerical results show that the bandwidth of flat band-

slow light can be effectively increased when the aspect ratio of the elliptical pillars is increased keeping filling factor constant.

Design and Waveguide Geometry



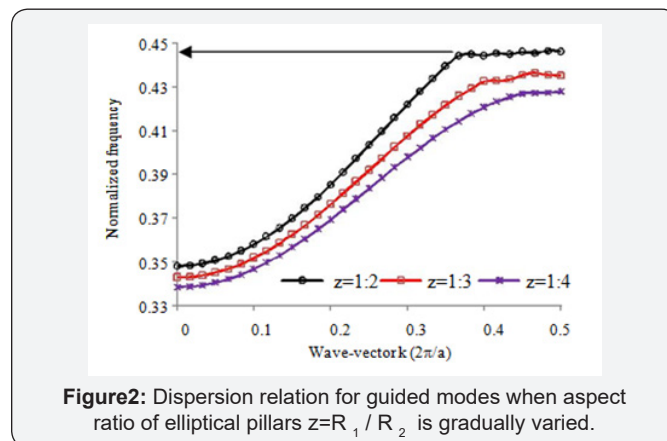
The proposed structure is composed of W1 waveguide which is formed by omitting one complete row of dielectric pillars. Figure 1 shows the schematics of proposed structure where the innermost row of circular nano pillars is replaced by elliptical nano-pillars, keeping filling factor same as circular pillars. PCW is laid down in x-z plane. Waveguide runs along the z axis. Filling factor is $\pi r^2/a^2$ where r is radius of circular pillars and 'a' is lattice constant. Radius of circular pillars away from waveguide axis is $r = 0.3a$ where $a=430\text{nm}$. The dielectric constant for nano-pillars is 11.56. Structure is being analyzed for changing axial ratio of dielectric pillars. Axial ratio or aspect ratio is defined as the ratio of major axis to minor axis.

Result Analysis and Discussion

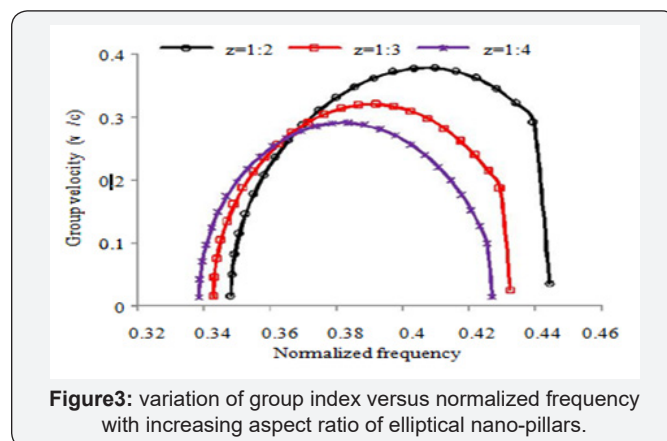
Because 3D analysis of the structure is very complicated and time consuming, 2 dimensional calculation of frequency band is carried out. Band gap region for a perfect photonic crystal with all circular nano-pillars extends from 0.2434 to 0.3177 in terms of normalized frequency (a/λ). Introduction of line defect in the perfect crystal leads to the generation of guided modes in the gap and thus, provides an efficient means to route the flow of light within the waveguide. Guided mode inside the waveguide is represented as sum of index guided and band-gap guided mode [9,10]. A strong interaction occurs between both the guided modes near the band edge that changes the linear nature of dispersion to parabolic nature at anti-crossing point [9,10]. Thus ultralow group velocity light is accompanied with large GVD effects. By changing the geometrical symmetry of waveguide, interplay between both the guided modes is perturbed in order to shift the position of anti-crossing point and to control large GVD effects [10-13].

In this paper, a single parameter (i.e. aspect ratio of elliptical pillars) is tailored to control the higher order dispersion effects. With changing aspect ratio of elliptical pillars, position of guided modes changes. A 2D plane wave expansion (PWE) method is used to calculate dispersion relation, with a resolution of 20

grid points per lattice constant [16]. Super cell method is used to investigate guided modes within band-gap [17] we, here only investigate the modes for which electric field is perpendicular to periodic plane. W1 PC waveguide is created in perfect crystal, which sustains guided modes inside photonic band gap and generates slow light at band edge. By changing the geometrical symmetry of the device, guided modes of the line defect based photonic crystal waveguide can be reshaped and thus leads to changing group velocity. Group velocity is defined as $vg = d\omega/dk$ where ω is angular frequency and k is wave-vector [13,14].



Row of circular nano-pillars, surrounding the waveguide core is replaced by elliptical nano-pillars and structure is analyzed for changing aspect ratio of elliptical pillars. Figure 2 shows the guided modes for changing aspect ratio of elliptical pillars. With increasing axial ratio guided modes are pulled downwards towards lower range of frequencies because dielectric constant locally increases in the waveguide core region by increasing minor axis of elliptical rods and this lowers the frequency of operation. Thus, light with specific optical frequency (solid arrow line in Figure 2) leads to reduction in group velocity along the direction of propagation for changing axial ratio until the waveguide no longer allows propagation.



Reduced velocity is measured by group velocity which is defined as local slope of dispersion curve $vg = d\omega/dk$ [13,18,19]. Figure 3 shows the variation of group velocity vg against normalized frequency for changing aspect ratio of elliptical nano-

pillars. When the aspect ratio of elliptical pillars is increased group velocity v_g decreases with corresponding decrease in bandwidth. The structure can be used as an optical buffer and its performance is measured by its buffering capacity which is quantified by normalized delay bandwidth product (NDBP) [1, 13,20]. NDBP is defined as

$$NDBP = n_g \times \frac{\Delta\omega}{\omega_0} \quad (1)$$

where $\Delta\omega/\omega_0$ is normalized bandwidth and n_g is group index, ($n_g=c/v_g$) which is assumed to be constant within $\pm 10\%$ of variation. NDBP (=0.3441) is achieved for an aspect ratio of 1:3.

Dispersion performance

Dispersion is an important issue for slow light devices. In the conventional W1 photonic crystal waveguide, signal is severely distorted by large GVD effects at band edge and results in pulse broadening. Structural tuning in conventional waveguide helps to compensate for dispersion effects [21-24]. GVD parameter is defined as in (2) where c is velocity of light, λ wavelength of signal, k is wave vector and ω is optical frequency of signal. Figure 4 shows calculated GVD parameter against normalized frequency for (Figure 1b).

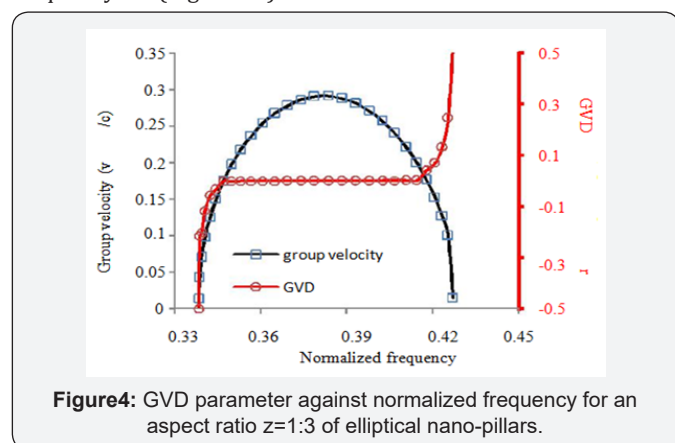


Figure4: GVD parameter against normalized frequency for an aspect ratio $z=1:3$ of elliptical nano-pillars.

$$GVD = -\frac{2\pi c}{\lambda^2} \frac{\partial^2 k}{\partial \omega^2} \quad (2)$$

GVD parameter is measured for an aspect ratio $z=1:3$. There exists a region of approximately zero dispersion which extends over large bandwidth ($\Delta\omega=12.4$ THz). Positive & negative dispersion peaks also exists in GVD curves due to 'U-shaped' group index curves. Thus structure can be utilized in dispersion compensating applications.

Conclusion

A new slow light device in a 2-dimensional lattice structure, using single line defect photonic crystal waveguide is investigated. Defect is introduced in a perfect crystal by omitting one complete row of pillars and replacing circular dielectric pillar with elliptical pillars nearest to waveguide core. Slow light

performance of the structure is tailored by increasing aspect ratio of elliptical pillars but keeping its filling factor constant. The reduced value of group velocity is reported for increasing aspect ratio of elliptical pillars. Figure of merit of the device is quantified by normalized delay bandwidth product. The increased value of normal delay bandwidth product (NDBP=0.3441) is obtained over an ultra large bandwidth ($\Delta\omega=12.4$ THz). The GVD parameter for the structure is also analyzed. The waveguide provides approximately zero dispersion over large bandwidth accompanied with positive & negative regions that opens the opportunity in dispersion compensating applications.

References

- Hao R, Cassan E, Le Roux X, Gao D, Do Khanh V, et al. (2010) Improvement of delay-bandwidth product in photonic crystal slow-light waveguides. *Op Express* 18(16): 16309-16919.
- Okawachi Y, Foster M, Sharping J, Gaeta A, Xu Q, et al. (2006) All-optical slow-light on a photonic chip. *Opt Express* 14(6): 2317-2322.
- Krauss TF (2007) Slow light in photonic crystal waveguides. *Applied Physics* 40(9): 2666-2670.
- Lukin MD, Imamoglu A (2001) Controlling photons using electromagnetically induced transparency. *Nature* 413(6853): 273-276.
- Bigelow MS, Lepeshkin NN, Boyd RW (2003) Observation of ultraslow light propagation in a ruby crystal at room temperature. *Phys Rev Lett* 90(11): 113903.
- Dai L, Jiang C (2009) Photonic crystal slow light waveguides with large delay-bandwidth product. *Applied Physics B* 95(1): 105.
- Joannopoulos JD, Pierre R, Shanhui Fan (1996) Photonic Crystal: Putting a new twist on light. *Nature* 386: 3787-3790.
- John DJ, Steven GJ, Robert D (2008) *Photonic Crystals: Molding the Flow of Light*. Princeton University Press, New Jersey, USA.
- Jamois C, Wehrspohn RB, Andreani LC, Hermannnd C, Hess O, et al. (2003) Silicon-based two-dimensional photonic crystal waveguides. *Photonics and Nanostructures Fundamentals and Applications* 1(1): 1-13.
- Jing M, Chun J (2008) Flat band Slow Light in Asymmetric Line-Defect Photonic Crystal Waveguide Featuring Low Group Velocity and Dispersion. *IEEE Journal of quantum electronics* 44: 8.
- Mori D, Baba T (2005) Wideband and low dispersion slow light by chirped photonic crystal coupled waveguide. *Opt Express* 13(23): 9398-9408.
- Daisuke M, Toshihiko B (2004) Dispersion-controlled optical group delay device by chirped photonic crystal waveguides. *Applied Physics Letters* 85(7): 1101.
- Hao R, Cassan E, Kurt H, Le Roux X, Marris-Morini D, et al. (2010) Novel slow light waveguide with controllable delay-bandwidth product and ultra-low dispersion. *Opt Express* 18(6): 5942-5950.
- Frandsen LH, Lavrinenko AV, Fage-Pedersen J, Borel PI (2006) Photonic crystal waveguides with semislow light and tailored dispersion properties. *Opt Express* 14(20): 9444-9450.
- Li J, White TP, O'Faolain L, Gomez IA, Krauss TF (2008) Systematic design of flat band slow light in photonic crystal waveguides. *Opt Express* 16(9): 6227-6232.
- Aaron JD (2005) *An introduction to the plane wave expansion method for calculating photonic crystal band diagram*. University of Illinois.

17. Smajic J, Hafner Ch, Rauscher K, Erni D (2004) Computation of radiation leakage in photonic crystal waveguide. Progress in Electromagnetic Research Symposium 28-31.
18. Jin H, Dingshan G, Huaming W, Ran H, Zhiping Z (2009) Flat Band Slow Light in Symmetric Line Defect Photonic Crystals Waveguide. IEEE Photon Tech Lett 21(20): 1571-1573.
19. Leng F-C, Liang W-Y, Liu B, Wang T-B, Wang H-Z (2010) Wideband slow light and dispersion control in oblique lattice photonic crystal waveguides. Optics Express 18(6): 5707-5712.
20. Nagesh JR, Rukhsar Z, Vijay J (2012) Improved design of photonic crystal waveguides with elliptical holes for enhanced slow light performance. Opt Eng 51(6): 064001.
21. Augustin M, Iliew R, Etrich C, Setzpfandt F, Fuchs HJ, et al. (2006) Dispersion properties of photonic crystal waveguides with a low in-plane index contrast. New Journal of Physics, pp. 8.
22. Notomi M, Yamada K, Shinya A, Takahashi J, Takahashi C, et al. (2001) Extremely Large Group-Velocity Dispersion of Line-Defect Waveguides in Photonic Crystal Slabs. Physical Review Letters 87: 253902.
23. Säynätjoki A, Mulot M, Ahopelto J, Lipsanen H (2007) Dispersion engineering of photonic crystal waveguides with ring-shaped holes. Opt Express 15(13): 8323-8328.
24. Janrao N, Zafar R, Janyani V (2013) Improved efficiency and enhanced slow light performance in photonic crystal waveguides using rectangular unit cells. Proc SPIE 8760 International conference on communication and electronics system design 8760.



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