

Slow light tunability in photonic crystals by defect layers

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Abstract

In present study, the effect of different defect layer refractive indices and thicknesses on group velocity has been studied in one-dimensional photonic crystal. It is found that the increase of refractive index, number of defects and defect layer thickness will induce the decrease of group velocity. Taking advantage of these results, a novel technique has been introduced to tune and control the slowing light in photonic crystal.

Keywords: Photonic Crystal (PC), slow light, tunability

1. Introduction

The speed of light in vacuum is usually denoted by c , and is approximately $3 \times 10^8 \text{ ms}^{-1}$, fast enough to circle the Earth's equator about 7.5 times in just one second. Data transmission with the speed of light is so advantageous in technology; however, it makes it difficult to control the optical signals in the time domain. Controlling the velocity of light is desirable for all-optical signal processing. Researchers are now developing an optical buffer that temporarily stores and adjusts the timing of optical packets [1]. This device is able to control all-optical processing and avoid the optical-electronic conversion that motivates a lot of inefficiency.

Slow light means reduction of group velocity of light. It offers the opportunity for compressing optical signals and optical energy in space, which reduces the device foot print and enhances light-matter interactions [2]. There are three main approaches for achieving Slow light; electromagnetically induced transparency [3], coupled resonator structures [4], and photonic crystals [5]. Photonic Crystals (PCs) have the advantage of small mode volumes and also, capability to integrate with other optical elements. In order to understand the physics of this device and explore its potential for tuning and controlling a low v_g , two important optical properties need to be considered; the frequency band width and higher order dispersion. There is a series of transmission resonances in the pass band in which, the PC exhibits low group velocity. It can be used to build compact optical delay lines for ultra short

electromagnetic pulses. Although a wide band width is desirable in most applications, it often comes at the price of less delay. Regarding the second issue, the high order dispersion that can be used as a delay line of pulses, distorts optical signals. The solution to overcome this limitation is often, using a coupled resonator optical waveguide, or combining two PCs with opposite dispersion characteristics.

After consideration of slow light in PC, the next important consideration is tunability. A variable v_g and delay were first demonstrated for band-edge slow light by externally controlling the material index [6]. After that, tuning of slow light pulse in PC coupled waveguide was achieved, and a visible time shift of pulses was observed by engineering the device structure and material index control [7].

In this study, the effect of different thicknesses and indices of refraction of dielectric defect layers on group velocity and dispersion of slow light in 1-D photonic crystal has been investigated, and this effect has been used for tuning slow light. Different theories and methods are proposed to investigate light propagation characteristics in PCs, such as T-matrix methods [5], equivalent layers theory [8] and Finite Difference Time Domain (FDTD) method [9, 10]. Here, FDTD method is being used to calculate transmittance, and then calculate group velocity of the structure.

2. Theory

To study the effect of defect layer parameters on group

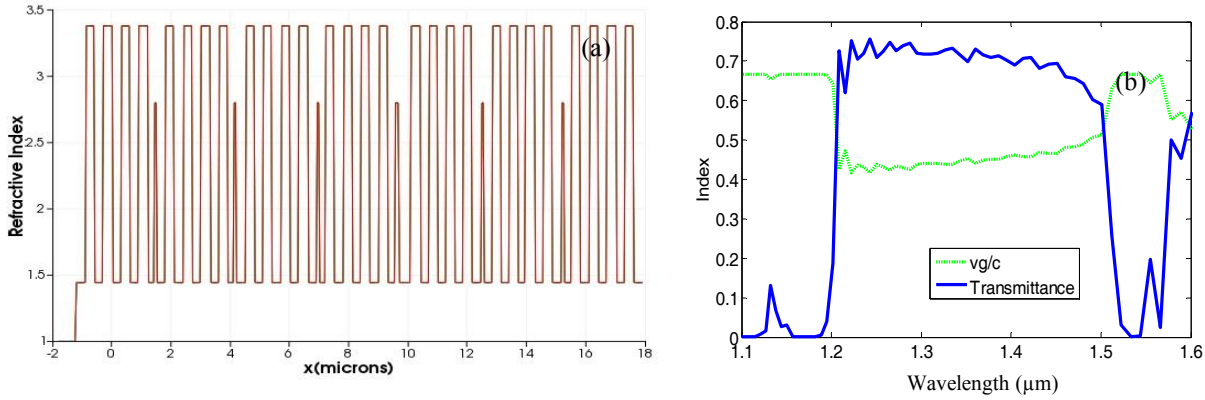


Figure 1. (a) Schematic illustration of the structure when the defect refractive index is $n_{\text{defect}}=2.8$. (b) Calculated transmission spectra and group velocity of the structure when $n_{\text{defect}}=1.5$.

velocity of PC, 1-D PC with basic structure of air/ ((LH)⁴LD)⁶(LH)⁴L /air is considered, where H and L denotes high index (GaAs) and low index (SiO₂) materials, respectively. The structure is illustrated in figure 1 (a). Calculated transmittance spectrum and group velocity factor of the structure when the defect layer refractive indices are considered to be equal to substrate ($n_{\text{defect}}=n_{\text{SiO}_2}$) are depicted in figure 1 (b).

It can be seen that the flat band in figure 1(b) is between 1.2 to 1.55μm. By replacing defects with different refractive indices, some fluctuations will be created on transmittance which leads to slowing down group velocity of light. It is known that light can be slowed down near resonances. Ultra- low group velocity is obtained near sharp resonances; however, other fluctuations allow us to present a demonstration of low group velocity which is more stable for the purpose of tuning. To understand the method, first the theory of calculating group velocity is being discussed, using transmittance curve. In a finite 1-D PC, the group index can be calculated by effective index approach. The effective complex refractive index is:

$$n_{\text{eff}}(\omega) = n(\omega) + ik(\omega), \tag{1}$$

This can be obtained by transmission coefficient,

$$t(\omega) = |t(\omega)|e^{ij(\omega)}, \tag{2}$$

n and k can be written as:

$$n(\omega) = \frac{cj(\omega)}{L\omega}, \tag{3}$$

$$k(\omega) = -\frac{c}{L\omega} \ln |t(\omega)|, \tag{3}$$

where L is the total thickness of PC. Group velocity v_g can be calculated by:

$$v_g = \frac{c}{n + \omega \frac{dn}{d\omega}}. \tag{4}$$

Using (3), group velocity of the device can be written as,

$$v_g = \frac{L\omega}{2j(\omega) + \omega \frac{dj(\omega)}{d\omega}}. \tag{5}$$

Using (5) group velocity of PC can be calculated using transmission.

It can be shown that group velocity of light in a

medium can be derived as:

$$v_g = \frac{d\omega}{dk}, \tag{6}$$

where ω is the angular frequency and k is the wave vector along the waveguide. Group Velocity Dispersion (GVD) is defined as derivative of inverse group velocity, then the coefficient of group velocity dispersion can be calculated by:

$$\beta = \frac{d\left(\frac{1}{v_g}\right)}{d\omega} = -\frac{1}{\left(\frac{d\omega}{dk}\right)^3} \frac{d^2\omega}{dk^2} = -\frac{1}{v_g^3} \frac{d^2\omega}{dk^2}. \tag{7}$$

The nature of delay and slow light in a PC waveguide is easily understood by considering light propagation in PC. Light is coherently backscattered at each unit cell of the crystal, so the crystal acts as a one-dimensional grating. If forward propagating and backscattered light agree in phase and amplitude, a standing wave results (as they do at Brillouin zone boundary), which can also be understood as a slow mode with zero group velocity. If we move away from Brillouin zone boundary, we enter the slow light regime; the forward and backward travelling components begin to move out of phase but still interact.

3. Result and discussion

PCs possess a band gap arising from multi-dimensional Bragg reflection. By placing a defect within an ideal PC, some fluctuations on the transmission spectrum appear which leads to fluctuations on the group index. Figure 2 shows the fluctuations of transmittance spectrum and the group velocity, when six defect layers are set in the structure of figure 1. The relevant defect refractive index value is set from 3.6 to 2.8. FDTD calculations show that light velocity is reduced from 0.7c to 0.07c. In fact, we have used the method of creating fluctuations in transmittance, to make a tunable system which can be tuned by changing the defect layer refractive index only.

To investigate the effect of number of defect layers on group velocity, we calculate this parameter when four defect layers, with different refractive indices, are placed in the structure. In this case, the structure can be defined

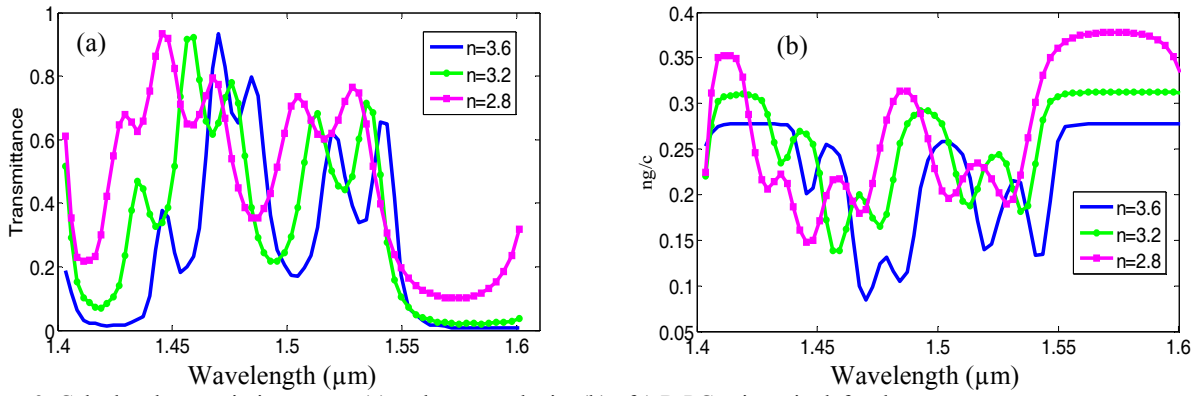


Figure 2. Calculated transmission spectra(a) and group velocity (b) of 1-D PC using six defect layers.

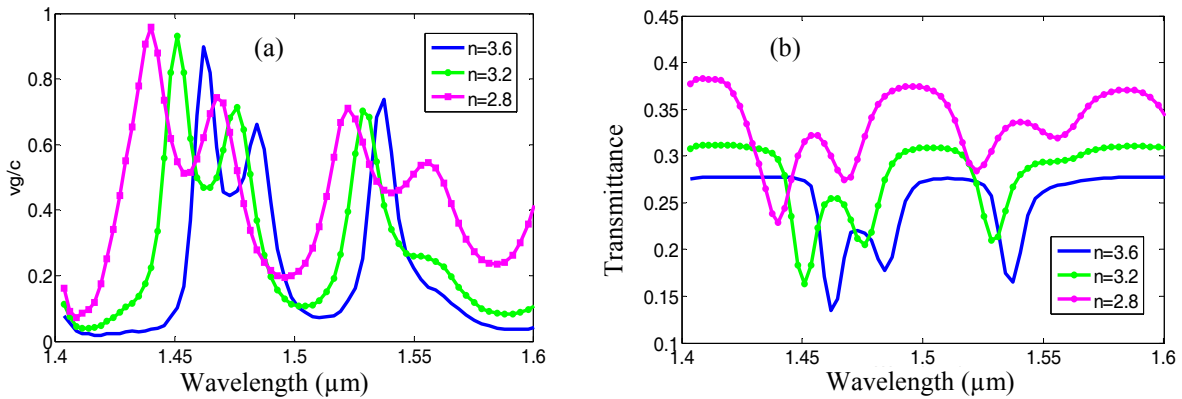


Figure 3. Calculated transmission spectra (a) and group velocity (b) of 1-D PC using four defect layers.

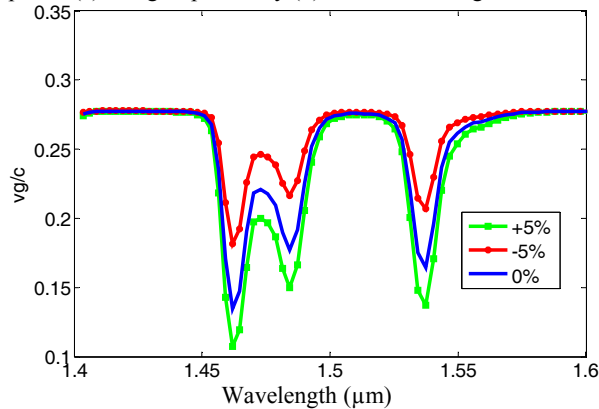


Figure 4. Group velocity changes with small violation of the defect thicknesses for four defect layers of $n=3.6$.

as $\text{air} / ((LH)^6 LD)^4 (LH)^6 L / \text{air}$. The results are depicted in figure 3. By comparing figures 2 and 3, it can be observed that by increasing the number of defects, the group velocity will decrease.

When the sample is fabricated, the slight violation of the thickness is inevitable, which will affect the properties of the slow light. We study the effect of slight violation when the thickness of the defect is decreased or increased by 5%. The result is shown in figure 4. This figure shows that group velocity variation is small, especially for the flat band parts, and there is no significant change.

It can be seen from figure 4 that when the defect layer is thickened, the group velocity is lowered.

Using eq. (7), it is obvious that the absolute value of GVD of the defect states is small. Thus, the width of

Gaussian pulse at the output end is approximately equal to that of the pulse at the input end, with very little pulse expansion. This result is useful to the optical delay line in optical network. GVD in the flat areas is also very small, for example for a Gaussian pulse at central wavelength of $\lambda_0=1.58\mu\text{m}$, GVD is calculated to be $0.48 \text{ ps}^2/\text{km}$. The incident pulse with a Full Width at Half-Maximum (FWHM) of 0.08 ps expands to 0.13 ps at the output. Due to this vanishing dispersion, the width of pulse at input end is nearly equal to that at output end and Gaussian pulse can be regarded as a plan wave [11].

4. Relation between group velocity and wavelength

Figure 5. plots the relationship between group velocity

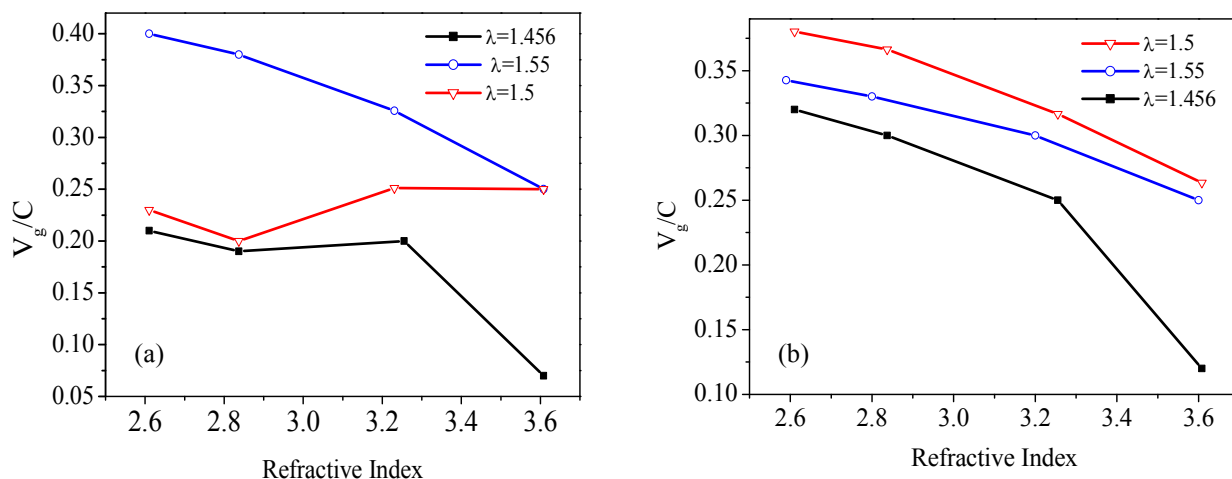


Figure 5. Group velocity of defect modes versus defect refractive index at different wavelengths. (a) with six defects (b) with four defects.

of the defect modes at different wavelengths and different defect refractive indices when four and six defect layers are placed.

To investigate group velocity variations versus defect refractive indices, two parts of transmittance spectrum; flat curves and sharp curves have been considered. For the case of flat curves, group velocity decreases with increase of the defect refractive index (1.5 μm to 1.6 μm in figure 3). But when considering the sharp points, it can be seen that small variations on the defect refractive index transfers transmittance spectrum

which leads to some unsmooth variations that is seen in figure 5 (b).

In conclusion, in this paper the effect of defect layers on the group velocity and dispersion properties of one-dimensional PC has been investigated. It has been shown that group velocity decreases with increasing refractive index, number and thickness of defect layers. Furthermore, a practical method to tune the group velocity of PC has been presented which does not need special media such as cold atomic gases, electronic transitions or nonlinear optical or thermal effects.

References

1. M L Povinelli, S G Johnson, and J D Joannopoulos, *Opt. Express* **13** (2005) 7145.
2. T. Baba, *Nature Photonics* **2** (2008) 465.
3. C Li, Z Dutton, C Behroozi, and L Hau, *Nature* **409** (2001), 490 .
4. M Settle, R Engelen, M Salib, A Michaeli, L Kuipers, and T Krauss, *Opt. Express* **15** (2007) 219.
5. A Yariv, Y Xu, R K Lee, and A Scherer, *Opt. Lett.* **24** (1999) 711.
6. Y A Vlasov, M O'Boyle, H F Hamann, and S J McNab, *Nature* **438**, (2005) 65 .
7. T Baba, T Kawasaki, H Sasaki, J Adachi, and D Mori, *Opt. Express* **16** (2008) 9245.
8. A Bananej, S M Hamidi, W. Li, C. Li, and M M Tehrani, *Opt. Mater.* **30**, 12 (2008) 1822.
9. A Taflove, S G Johnson, and A Oskooi, "Advances in FDTD Computational Electrodynamics: Photonics and Nanotechnology," Artech House, Norwood, MA (2013).
10. H Tian and Y Ji, *Mod. Phys. Lett. B* **23**, 8 (2009) 1053.
11. S Rawal, K Sinha, and M De La Rue, *Opt. Express* **17** (2009) 552.