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Wideband and Low Group Velocity in a Novel Photonic Crystal Waveguide

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Abstract　A novel slow light photonic crystal waveguide is proposed by introducing two additional adjacent holes into the single line-defect structure. Influences of the boundary row shifts and the additional holes′ distance on the device performances are investigated in detail. Compared with the boundary row shifts method, a better slow light property can be obtained by modifying the distance of two additional adjacent holes. Numerical results demonstrate that the group velocity is reduced to $0.03c$ (c is the light velocity in vacuum) under nearly the same operational bandwidth.

Key words　optical communications; slow light; photonic crystal waveguide; group velocity; bandwidth

OCIS codes　230.7370; 210.4810; 260.2030

宽带低群速度新型光子晶体慢光波导

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摘要　利用在单线缺陷结构中引入两个附加的相邻介质柱构成一种新型的光子晶体慢光波导结构，并且详细研究了平移缺陷边界介质柱以及改变缺陷内附加的相邻介质柱间距对器件性能的影响。结果表明：与平移缺陷边界介质柱相比，通过改变缺陷内附加的相邻介质柱间距可以获得更好的慢光特性，即在保持有效带宽基本不变的情况下，将光群速度降低到 $0.03c$（c 为真空下的光速）。

关键词　光通信；慢光；光子晶体波导；群速度；带宽

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1　Introduction

Photonic crystal waveguides (PCWs), which give a wide range of applications in the field of slow light and optical storage, have been heavily investigated for several years[1-3]. Slow lights in PCWs attract more and more attention recently because the features of slow lights in PCWs are not determined by the natural material dispersion. PCWs with suitable design can obtain extremely reduced group velocity flexibly[4-8]. However, the bandwidth is narrowed and huge group velocity dispersion is arisen when the light is slowed down. As a result, the waveforms of high speed optical signals are deformed severely[1,9-11].

Up to now, two main solutions in photonic crystal waveguide structures have been put forward to remove the disadvantages due to limited bandwidth and large dispersion in slow light. The first method is associated with modifications of the structure parameters close to the waveguide core in a single line-defect PCW[3-5], and the linear dispersion curves have been achieved by adjusting the geometry of photonic crystal, such as changing the hole size or hole position of the first row[4-5,9], or by introducing annular holes into the whole lattices[11-13]. The second method is based on dispersion compensation, using photonic crystal coupled waveguides to gain a flat band at an inflection point and then move it in a chirped structure[14-17]. In previous papers, a folded chirped PCW was used to reduce propagation spectra oscillations[18].

In this paper, a novel slow light PCW is proposed by introducing two additional adjacent holes into the single line-defect structure. Merits of the novel structure are its slower group velocity and much wider operational bandwidth.

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2 Structure design

The proposed structure starts from a single line-defect PCW, which is obtained by removing a line defect in a Si air bridge slab photonic crystal (PC) consisting of the oblique lattice, where the effective refractive index of Si is 3.4. Then two additional adjacent holes are set in the waveguide of each period. The whole structure still keeps the cyclical character and can be fabricated. The distance of each two adjacent holes L plays a key role in the following structure optimization. Moreover, the two rows of air holes upon the line defect are deliberately shifted by $\mathrm{d}x$ distance along the x axis direction and $\mathrm{d}y$ distance along the y axis direction. The influence of structure parameters $\mathrm{d}x$ and $\mathrm{d}y$ on the character of slow light will be discussed in detail in the following paragraphs. Indices for air and silicon layer are 1.0 and 8.9, respectively. Radius of the air hole is $0.49a$, where a is the PC lattice constant. The whole structure is depicted in Fig.1.

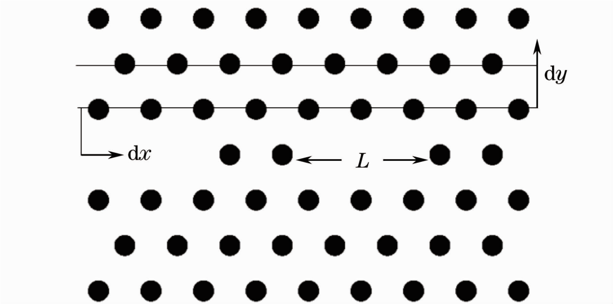

Fig.1 Schematic picture of the proposed PCW geometry

Obviously, the whole structure can be treated as a one-dimensional corrugation. The shifting of the two bordering of holes introduces another one-dimensional variation, which drastically changes the slow light nature.

The dispersion relations are calculated using the two-dimensional (2-D) plane wave expansion (PWE) with slab equivalent index method. The accuracy of this method is good enough to analyze the slow light property in slow light regime.

3 Analysis and discussions

To understand the shifting effect on band properties, the influence of $\mathrm{d}x$ on the waveguide dispersion curves is studied by the PWE method. The transverse-electric (TE)-like polarization mode which means magnetic field parallel to the vertical direction is calculated. As the computational cost of three-dimensional simulations is huge, two-dimensional simulations are shown here.

Figure 2 shows the dependences of main TE photonic band on the various structure parameters, including angular frequency $\omega = a/\lambda$, wavenumber $k = 2\pi/a$. It can be seen that the change of $\mathrm{d}x$ and $\mathrm{d}y$ will directly reflect in the band curves. Fig. 2(a) illustrates the shifting tendency of the photonic bands when $\mathrm{d}x$ is gradually changed with $\mathrm{d}y=0$. When $\mathrm{d}x$ is increasing, the slope of the band gradually turns to more and more flat in the wave vector range. Therefore, the group velocity, defined as $v_g = \mathrm{d}\omega/\mathrm{d}k = c/n_g$ [c is the light velocity in vacuum, $n_g = n + \omega(\mathrm{d}n/\mathrm{d}\omega)$ is the group index], is slowed down. Similarly, Fig.2(b) shows the variation of the photonic band by adjusting $\mathrm{d}y$. When $\mathrm{d}y$ is increasing, the slope of the band undergoes similar as shown in Fig. 2(a). However, comparing Fig.2(b) with Fig. 2(a), it can be seen that the photonic band slope is more sensitive to the tuning of $\mathrm{d}y$. The phenomenon can be explained as follow: the band curve of PCWs is generally made up of two parts of the index-guide mode part and the gap guide mode part[19]. When the two rows of air holes bordering the line defect is shifted, the hole density of whole structure is affected and the gap-dominated mode is enlarged. As the hole density of the photonic crystal lattice is increasing, the optical energy can be pushed out of the waveguide core, thus spreading in the lateral direction. It can be seen from the overall structure that shifting the two rows of air holes upon the line defect along x direction expands the line defect and has larger effect on hole density than along y direction. Therefore, a larger group index n_g and a slower group velocity v_g are obtained. Fig. 3 illustrates the group velocity v_g curves under the tuning of $\mathrm{d}x$ and $\mathrm{d}y$. All the calculated group velocity curves show similar

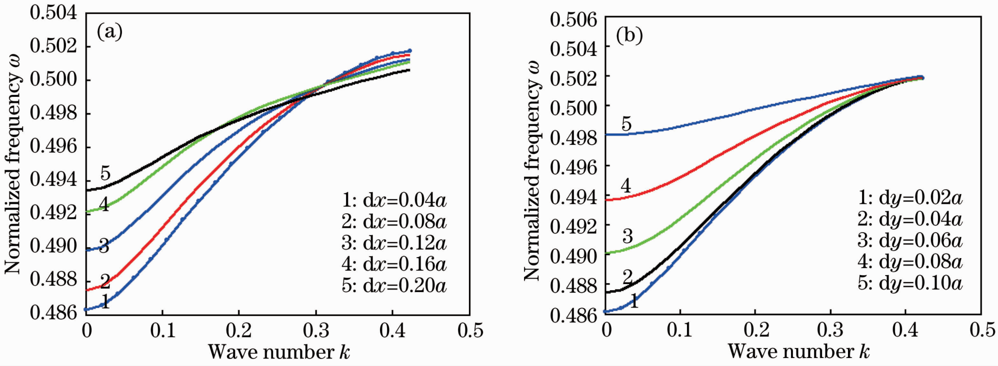

Fig.2 TE photonic band varying with the parameter (a) $\mathrm{d}x$ or (b) $\mathrm{d}y$ tuning

parabolic forms. With the tuning of dx or dy, a relative flat region is found in the curve center and the whole curve is reduced, which means a slower group velocity is realized.

In addition, the group velocity dispersion (GVD) [defined as $\beta = \mathrm{d}(1/v_g)/\mathrm{d}\omega$] is another important performance factor for the PCWs. The large GVD distorts the waveforms of high speed optical signals severely. Therefore, it is important to realize slow light structure with low dispersion property.

Figure 4 gives the calculated GVD of the proposed structure. It can be seen that there exists a bandwidth where the trend of the curves is relatively stable and the GVD value of the frequency area is nearly zero. Comparing with Ref. [4], the bandwidth of "zero" dispersion of the proposed structure is larger, which shows the advantage of the structure in dispersion. When dx or dy is increasing, the curves come to shift to the right slightly and the effective bandwidth becomes narrow. Therefore, using the boundary row shifts dx or dy method, the slower velocity, the smaller GVD and the broader bandwidth can not be obtained simultaneously.

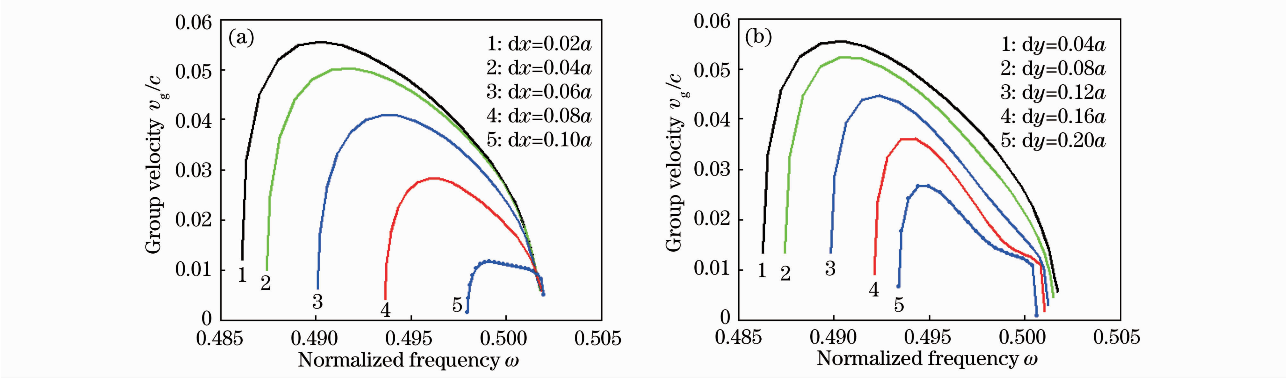

Fig. 3 Group velocity curves with different parameters of (a) dx and (b) dy

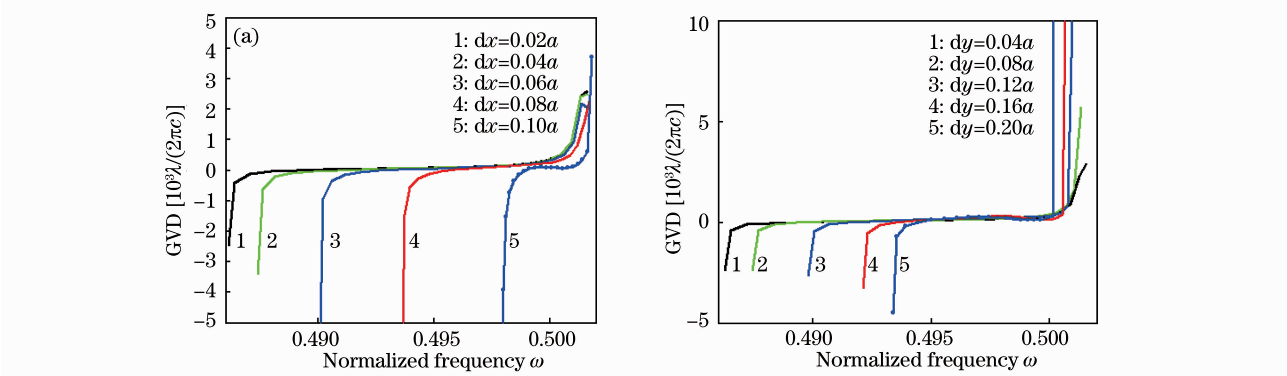

Fig. 4 GVD curves obtained for different values of (a) dx and (b) dy waveguide geometry parameter

In order to solve the paradox mentioned above, the distance of additional adjacent holes L is investigated. Research results demonstrate the photonic band slope gradually turns to more and more flat as L is increasing, similarly to the tuning of dx or dy. But, on the other hand, different from the boundary rows shifting method, the group velocity curves are reduced without narrowing the operational bandwidth as obvious as the tuning of dx or dy. From Fig. 5, it can be seen that the group velocity is reduced from $0.05c$ to $0.03c$ meanwhile maintaining nearly the same operational bandwidth. Therefore, we can come to a conclusion that the better slow light PCW structure with lower group velocity and broader bandwidth can be achieved by tuning of the additional adjacent holes distance L. According to the calculation, the normalized delay-width product (NDBP) in the condition of d$x = 0.06a$, d$y = 0.04a$, $L = 6a$, is 0.341. Compared with Ref. [20],

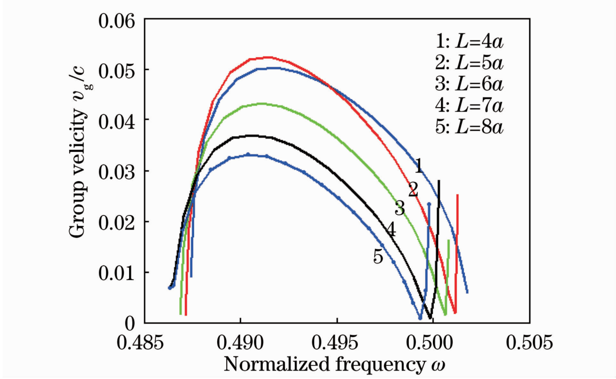

Fig. 5 Group velocity curves with different values of parameter L

the NDBP value has increased by 15% while the group velocity of the proposed structure is lower.

4 Conclusion

A novel PCW structure is proposed to obtain slow waves in the largest possible bandwidth and lowest group velocity dispersion. The proposed structure is based on removing a line defect in a slab oblique lattice photonic crystal and setting two additional adjacent holes in every period. By shifting the bordering air-hole row dx or dy, a slower group velocity is obtained but at a cost of narrowing operational bandwidth. However, by modifying the distance of two additional adjacent holes L, a better slow light property with lower group velocity and broader bandwidth is achieved. Unlike dx and dy, the change of L allows a lower velocity without much loss of effective frequency bandwidth. By proper selection of dx, dy and L, the contradiction between group velocity and bandwidth can be solved. The slow light devices based on photonic crystal lattices can be optimized in the same way.

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