Chinese Journal of Physics 55 (2017) 2318–2324

Contents lists available at ScienceDirect

Chinese Journal of Physics

journal homepage: www.elsevier.com/locate/cjph

Geometrically tunable slow light based on a modified photonic crystal waveguide

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ARTICLE INFO

Keywords:
Photonic crystal
Waveguide
Slow light

ABSTRACT

In this paper, we have proposed a design for slow light in a modified photonic crystal waveguide by inserting reduced air holes along the middle of the waveguide with a half period of the lattice and by shifting the second rows of holes toward the center of the modified waveguide. A wideband slow light with a high group index and low group velocity dispersion has been achieved. A nearly constant group index of 21, 20, 35.5 and 65 over 20.3 nm, 15.6 nm, 9.5 nm, 5.3 nm bandwidth in the environment of 1550 nm, respectively, are also obtained.

1. Introduction

Photonic crystals are periodically structured electromagnetic media, generally possessing photonic band gaps (PBGs): certain frequencies do not pass through the structure [1]. PBG structures have appeared in several scientific and technical areas and various devices [2] such as filters [3], optical switches [4], optical waveguides [5], cavities [6], and sensors [7]. A few years ago it was found that photonic crystals waveguides (PhCWs) can have a low group velocity away from the band edge [8], this property, which was named "slow light", attracted wide attention due to its wide applications. Slow light promotes a stronger light–matter interaction; it offers additional control over the spectral bandwidth of the interaction, and it allows us to delay and temporarily store light in all-optical memories. It is also anticipated that it can enhance linear and nonlinear effects and so miniaturize functional photonic devices, because slow light compresses optical energy in space, as a light pulse enters a photonic-crystal waveguide operating in the slow-light regime the pulse length is compressed, resulting in an increased intensity [9–11]. Two of the key concerns are propagation loss and dispersion, as any benefit arising from slow light may be compromised by excessive loss or pulse broadening [12]; the group velocity is usually strongly dependent on the frequency. This effect is quantified by the group velocity dispersion (GVD). Since every optical pulse has a certain spectral content, an optical pulse will experience a broadening due to the GVD, which removes most of the advantages of operating in the slow light regime and severely limits the bandwidth that can be utilized. However, this behavior is not an intrinsic property of the structure, but is subject to design. Designs that are based on a better understanding of slow light operation can overcome this limitation; this so-called dispersion control of pulses in PhCWs is one of the promising applications of photonic crystals [13,14]. Slow light in photonic crystal waveguides can be used for a wide range of applications, such as delay lines or buffers and enhanced light-matter interaction, both in the linear and nonlinear regime [15]. Previously, dispersion engineering methods have been proposed, such as perturbing the holes adjacent to the waveguide core [16], chirping the waveguide properties [17], changing the position of the first two rows of holes adjacent to the line defect [18], ellipse-shaped holes [19] or eye-shaped air holes [20].

Considering the previous methods, some of them leading to good results in theory, but needing much more difficult fabrication

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http://dx.doi.org/10.1016/j.cjph.2017.09.015
Received 28 June 2017; Received in revised form 26 September 2017; Accepted 27 September 2017
Available online 10 October 2017

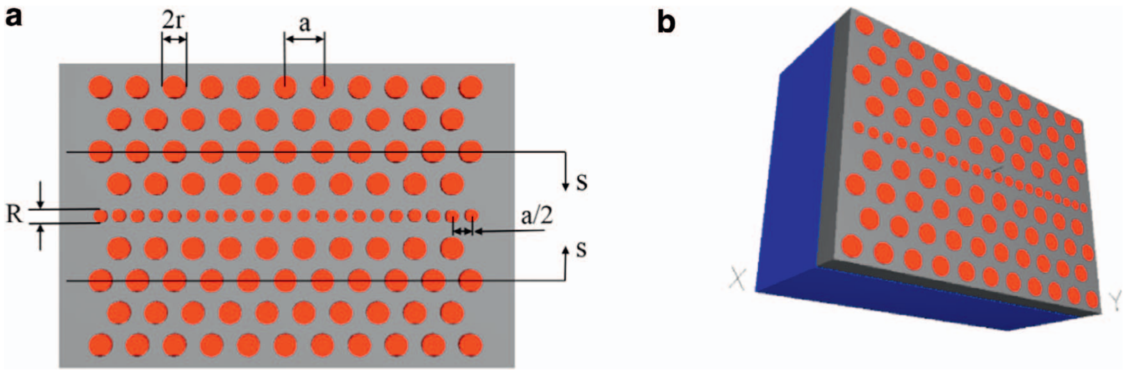

Fig. 1. Schematic representation of the proposed modified photonic crystal waveguide with reduced air holes in the middle of the waveguide, (a) the 2D modified photonic crystal waveguide with $n_{eff} = 3.2$, (b) photonic crystal slab in 3D.

technologies, while others are difficult to control.

In this paper, we explore a simple and technologically preferable method for achieving slow light. Shifting air holes is one of the simplest methods in terms of control and fabrication, therefore, the proposed method lies in inserting reduced air holes with a half period in the middle of the waveguide and shifting only the second rows of air holes adjacent to the center waveguide, while keeping the position of the first rows unchanged. The paper focuses on reducing the unwanted dispersion by engineering the dispersion curve, with the aim of achieving a constant group index over a broad wavelength range.

2. The proposed structure

In this paper, a design of a modified photonic crystal waveguide is proposed and shown in Fig. 1(a). It is a triangular lattice photonic crystal slab consisting of circular air holes of radius $r = 0.3a$, where $a = 400$ nm is the lattice constant, embedded in a silicon-on-insulator (SOI) substrate ($n_{si} = 3.48$) with a 410 nm thickness. The silicon slab has been bounded by an upper cladding layer of air and a lower cladding layer of silica (SiO_2). The x-axis is parallel to the line defect and the y-axis is perpendicular to the line defect of the waveguide.

The waveguide (W1) is formed by replacing the central row of air holes in the triangular lattice photonic crystal along the Γ-K direction with successively reduced air holes with a half lattice constant ($a/2$). Three-dimensional photonic crystals (PCs) with a complete band gap are ideal candidates for these applications, but their fabrication is challenging. An alternative solution is the photonic crystal slab (PCS) because of their relative ease of fabrication, their photonic band gaps lie in the x-y plane, and the index differences are used to confine the light vertically (total internal reflection). But full three-dimensional calculation and simulation of such complex devices are very time consuming and make extreme demands on computer memory. To deal with this drawback, the effective index method (EIM) [21] has been widely used to reduce the actual 3D problem shown in Fig. 1(b) to a 2D one.

The effective refractive index for our photonic crystal slab has been calculated to be 3.2.

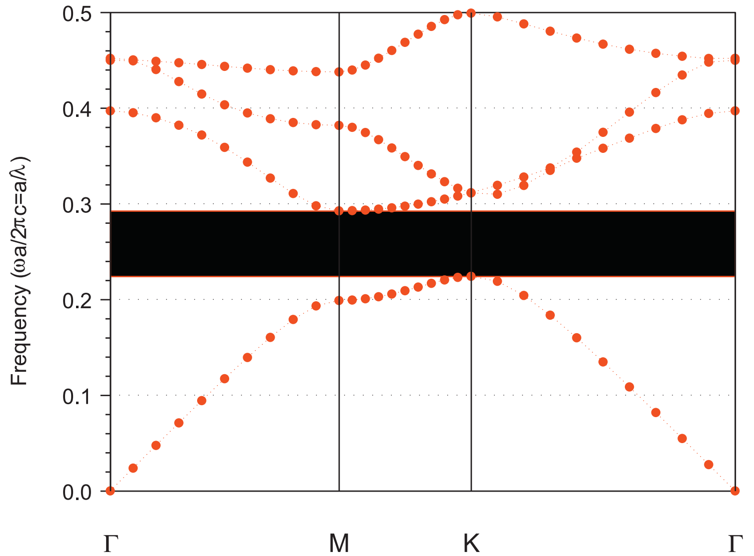

Fig. 2. Dispersion diagram and band gap for the TE polarization for the 2D triangular lattice of air holes without defects.

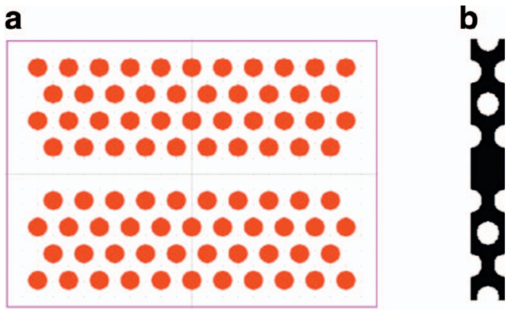

Fig. 3. (a) Schematic picture of the W1 line-defect waveguide with $r = 0.3a$ and lattice constant $a = 0.4$. (b) The periodic supercell for simulation analysis.

The most important property of the photonic crystals is the band gap. Fig. 2 shows the calculated band diagram for the initial PC structure consisting of circular air holes; it has been calculated along the Γ-K-M-Γ edge for the Brillouin zone (BZ) by employing a 2-D plane wave expansion (PWE) method of the RSoft (BandSOLVE) software. The structure exhibits a photonic band gap for TE polarization in the normalized frequency range of 0.2241 ($\omega a/2\pi c$) and 0.2926 ($\omega a/2\pi c$).

Using triangular PhCs is very advantageous, since they have a large bandgap with the TE polarization, and it is a good platform for photonic integrated circuits, optical sensors, and miniaturized optical devices [22].

Preliminary, we study the simplest form of a waveguide line-defect waveguide as shown in Fig. 3(a), which is obtained by removing a row of holes along the Γ-Kdirectionof a 2D triangular lattice photonic crystals with cylindrical air holes in silicon. Fig. 3(b) shows the selected supercell, since the photonic crystal structure is still perfectly periodic in the X direction, we use one row of air holes along the X-axis, but we need to include more rows along the Y-axis, hence 8 rows of air holes in the Y direction, which is adequate for the eigenmodes calculation.

The dispersion diagram for the W1 has been shown in Fig. 4(a) which exhibits two guided modes, the odd and even modes by solid blue and red curves, respectively, existing below the silica light line. Only the dispersion region below the light line could confine light well in the vertical direction of the slab, whereas modes above the light line become leaky. The linear dispersion curve of the even mode has a wide range of wave vectors, therefore, in this paper we discussed only the vertically even transverse electric like modes.

By using the 2D finite difference time domain (FDTD) method we obtained the electric field distribution of the even mode shown in Fig. 4(b), it is clear that the energy is concentrated in the line defect of the waveguide due to the symmetric constraint.

The group velocity $v_g = d\omega/dk = c/n_g$ of the light wave can be calculated from the slope of the dispersion curve, where k and ω are the wave vector and the light frequency, respectively. n_g and c are the group index and the speed of light in vacuum, respectively. The group velocity dispersion GVD is defined as the derivative of the inverse group velocity $d({v_g}^{-1}) = d^2k/d\omega^2$.

In Fig. 4(a) we see that the normalized frequency of the even mode at the band edge is $\frac{\omega a}{2\pi c} = 0.23042$, which means that the wavelength at the band edge is $\lambda = 1735$ nm ($\frac{\omega a}{2\pi c} = \frac{a}{\lambda}$ where λ is the wavelength), so the group index will extremely increase at this frequency, and the speed of the light wave is slowing very dramatically. The group index has been calculated for the basic photonic crystal waveguide W1, as shown in Fig. 5(a). As we can see, the group index varies rapidly in the slow light region, which means that we have a narrow bandwidth and large group velocity dispersion GVD on the order of 10^8 ps^2/km near the band edge; the optical

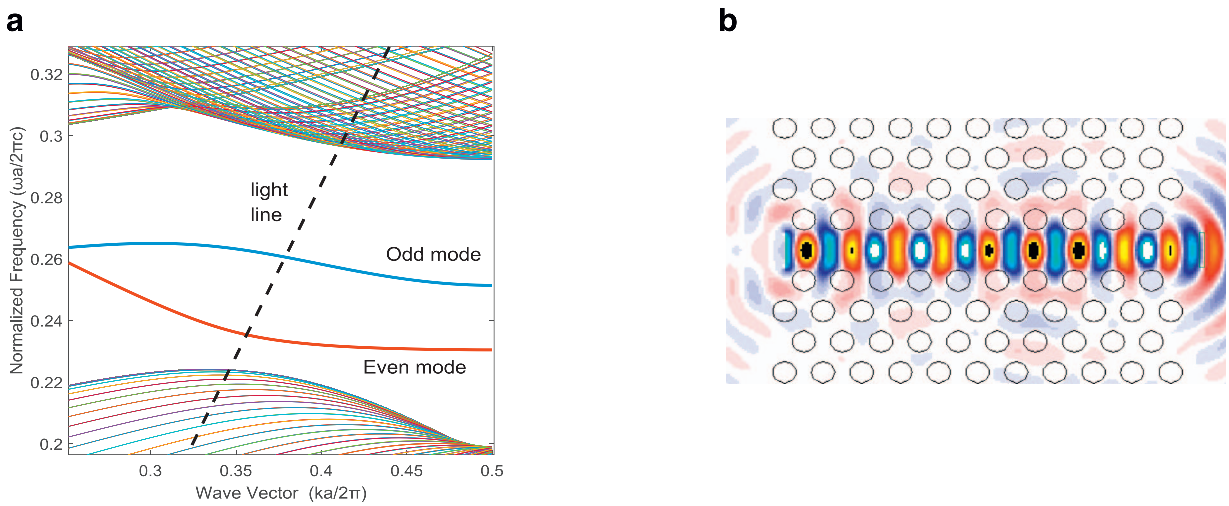

Fig. 4. (a) Calculated dispersion diagram of the basic W1. (b) The electric field distribution of the basic W1. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

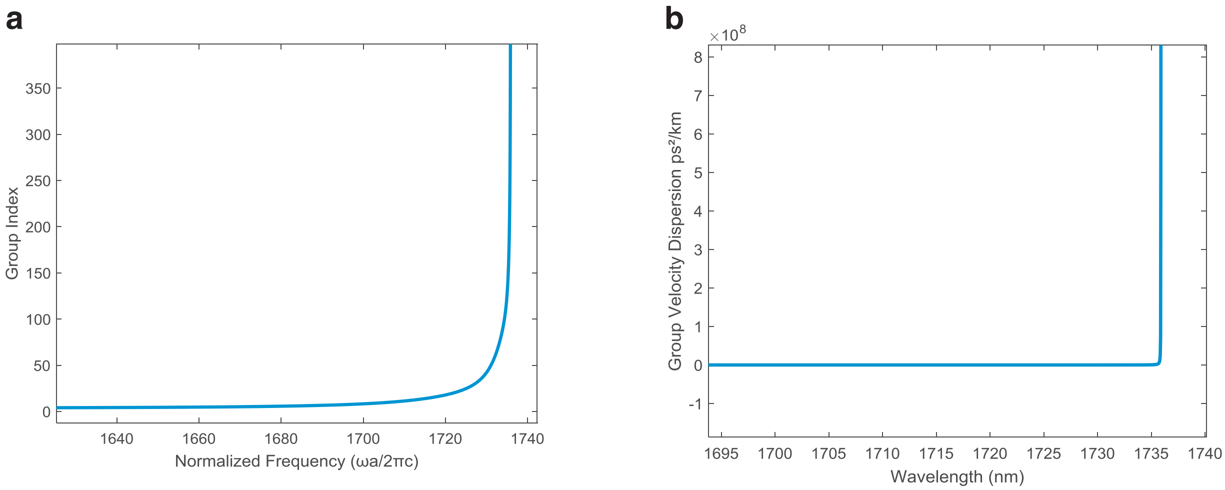

Fig. 5. (a) The group index curve of basic waveguide W1. (b) The group velocity dispersion versus the wavelength.

signals propagating through such waveguides will experience broadening.

Fig. 6(a) presents the modified photonic crystal waveguide; we removed the middle row of holes of the waveguide and replaced it with a row of air holes separated by a distance of half lattice constant $a/2$ nm, we need to find a guided mode near the 1550 nm at the band edge ($ka/2\pi = 0.5$), this ensures a wideband of slow light in the vicinity of the operation wavelength 1550 nm, to achieve this we have changed the radius of the air holes in the center of the waveguide in order to obtain the required guided mode.

Fig. 6(b) Shows the supercell selected with one row of air holes in the X direction and 8 rows of air holes in the Y direction for calculating the dispersion diagrams.

Fig. 7 shows the variation of the guided modes versus the radius of the reduced air holes in the middle of the modified photonic crystal waveguide. It has been observed that the even modes shift towards the higher frequency when the reduced air holes in the waveguide center along the propagation direction increases from $R1 = 0.105a$ to $0.2325a$. We found that the radius $R1 = 0.17a$ is an optimum value of the reduced air holes, which leads to the guided mode (even mode for the optimized structure) in the vicinity of the wavelength 1550 nm at the band edge ($ka/2\pi = 0.5$), as shown in Fig. 8. The solid red curve within the gap illustrates the even mode propagating along the waveguide, whereas the dashed black line is showing the photonic crystal light line.

By taking $R1 = 0.17a$ nm, the group index and the group velocity dispersion parameter have been calculated and plotted, as shown in Fig. 9(a).It is evident that the group index in the slow light region lies at the wavelength 1550 nm area, and, as expected, the corresponding group velocity dispersion GVD shown in Fig. 9(b) is lower than the photonic crystal waveguide W1, and it is in order of 10^6 ps^2/km.

3. Simulation, results, and discussion

The aim of our work is to achieve a slow light regime with high group index, wide bandwidth, and low GVD. We have studied the influence of the displacement of the air holes position; therefore, we keep the first rows of air holes unchanged and shift the positions of the air holes in the second rows on both sides of the line defect in opposite directions toward the center of the waveguide, in order to modify the dispersion curve. As shown in Fig. 6(a), the S parameter describes the deviation relative to the unmodified lattice; we optimized this parameter (S) to tailor the shape of the modified PhCW dispersion curve. Fig. 10(a) shows the normalized frequency $\frac{\omega a}{2\pi c}$ as a function of the wavevector $ka/2\pi$ of the even mode when S is varied for optimization. It can be found that there exists a linear

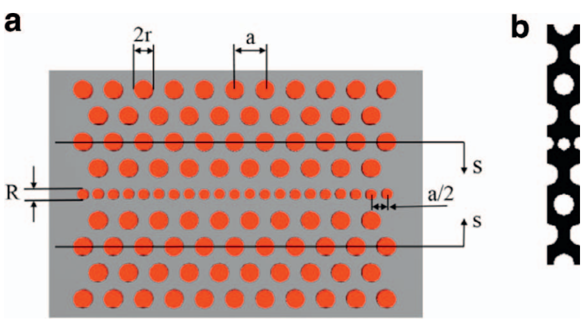

Fig. 6. (a) The modified photonic crystal waveguide. (b) The supercell of the modified waveguide with 1 row of air holes in the X direction and 8 rows of air holes in the Y direction.

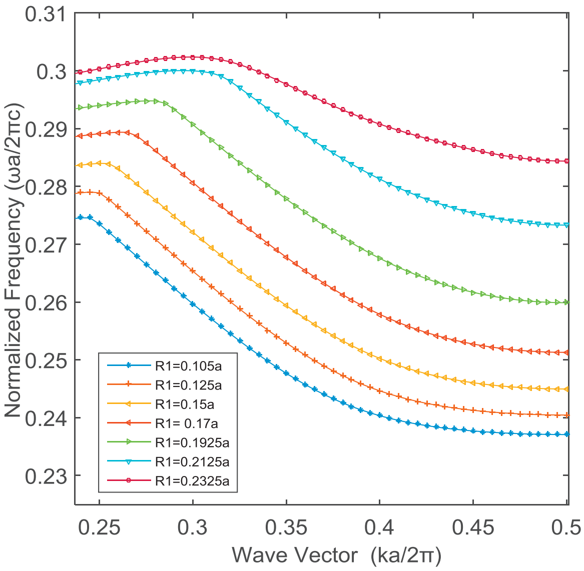

Fig. 7. Variation of dispersion curve with the radius $R1$ from $0.105a$ to $0.2325a$ of the reduced air hole in the middle of the modified photonic crystal waveguide.

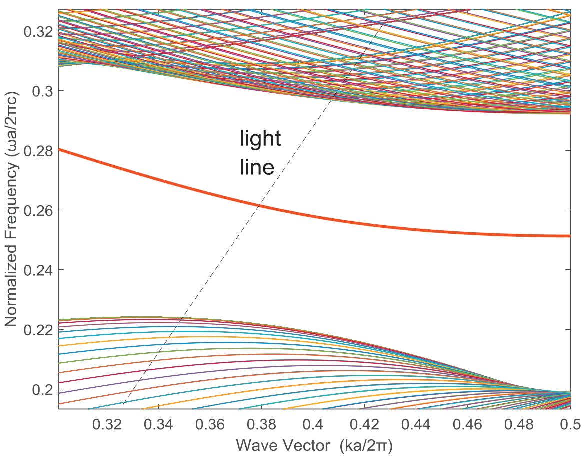

Fig. 8. Dispersion curve of the even mode for the optimized structure with $R1 = 0.17a$. (For interpretation of the references to color in the text, the reader is referred to the web version of this article.)

region of each curve corresponding to a flat band slow light region with a specific group index n_g determined by its slope. The flat band region represented with a thick solid black lines. As we see, the dispersion curves shifts to lower frequency with S increased, and the shift becomes more rapid near the tail of the dispersion curve. Fig. 10(b) shows the calculated group indices as a function of the wavelength; we can clearly see that the slow light of the modified photonic crystal waveguide possesses a "wideband slow light" region where the group index is nearly constant. In order to evaluate the dispersion bandwidth of the slow light, some previous papers select a bandwidth criterion, where the group index n_g was considered as constant within ± 10% range; the simulation results according to this criterion demonstrate nearly constant group indices of 21, 20, 35.5 and 65 while their corresponding bandwidths can reach20.3 nm, 15.6 nm, 9.5 nm, 5.3 nm, respectively, which we represent with a thick solid black lines. We also observe that when the S parameter increases the group index decreases and shifts to a higher working wavelength, besides the slow light bandwidth becomes wider.

The second order dispersion is known as the group velocity dispersion GVD ($\beta_2 = d^2 k/d\omega^2$), we have calculated this parameter for two values of the parameter S ($0.325a$, $0.2775a$), as shown in Fig. 11(a) and (b).The group index curve and the corresponding dispersion group velocity curve of the slow light flat region for the modified PCW are lower than 10^5 ps^2/km, which is one order of magnitude smaller than that of the basic photonic crystal waveguide W1.

The operational wavelength can be tuned over a large range from 1544 nm to 1574 nm, (where the 1544and 1574 nm are the working wavelengths of the wideband slow light, as shown in Fig. 10(b)) by shifting only the second rows with the S values calculated previously (Table 1).

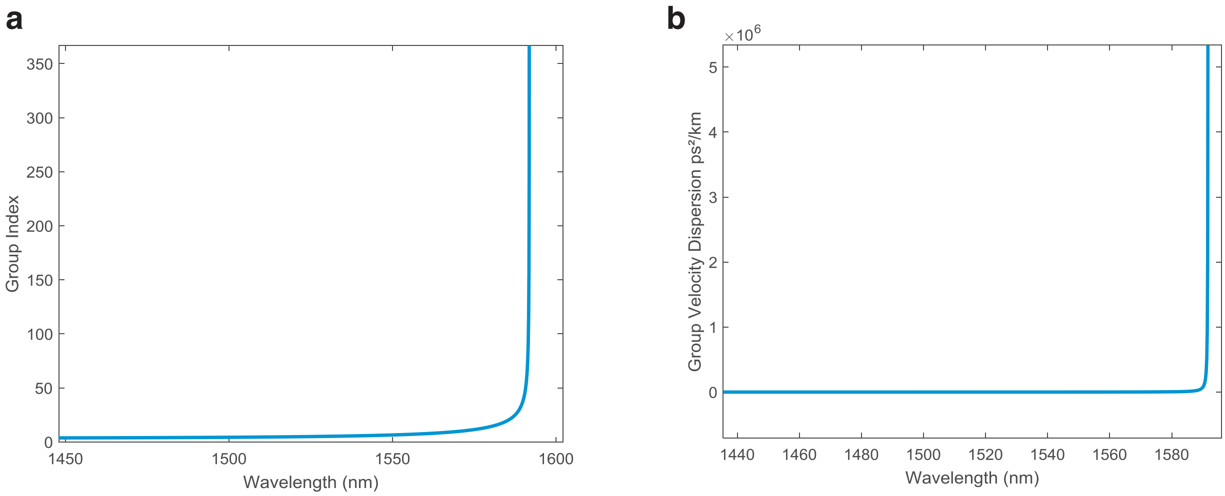

Fig. 9. (a) and (b) Group index and group velocity dispersion for the modified photonic crystal waveguide with $R1 = 0.17a$.

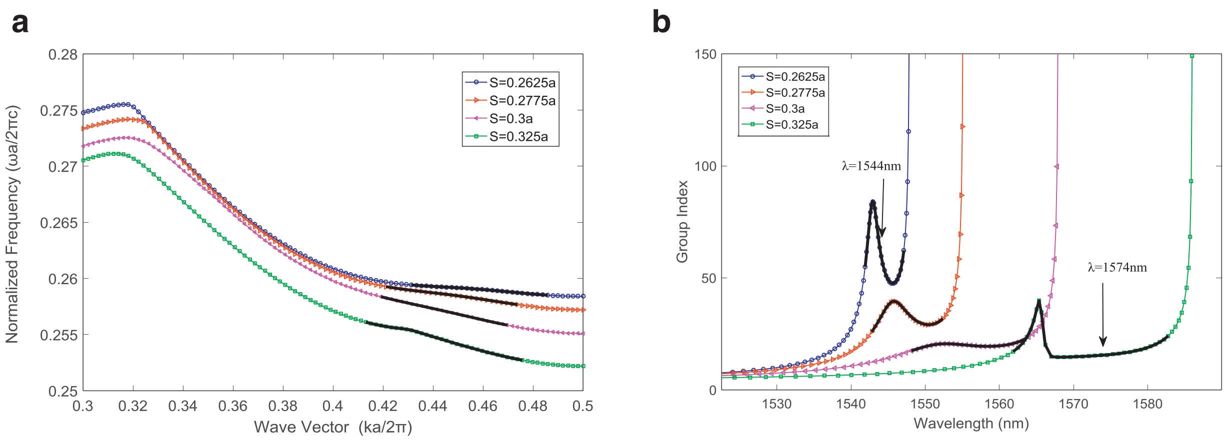

Fig. 10. (a) Calculated dispersion curves of the modified photonic crystal waveguide. (b) The corresponding group indices for the fundamental mode of the modified PCW for different values of the S parameter, the thick solid black line represents the flat band slow light region.

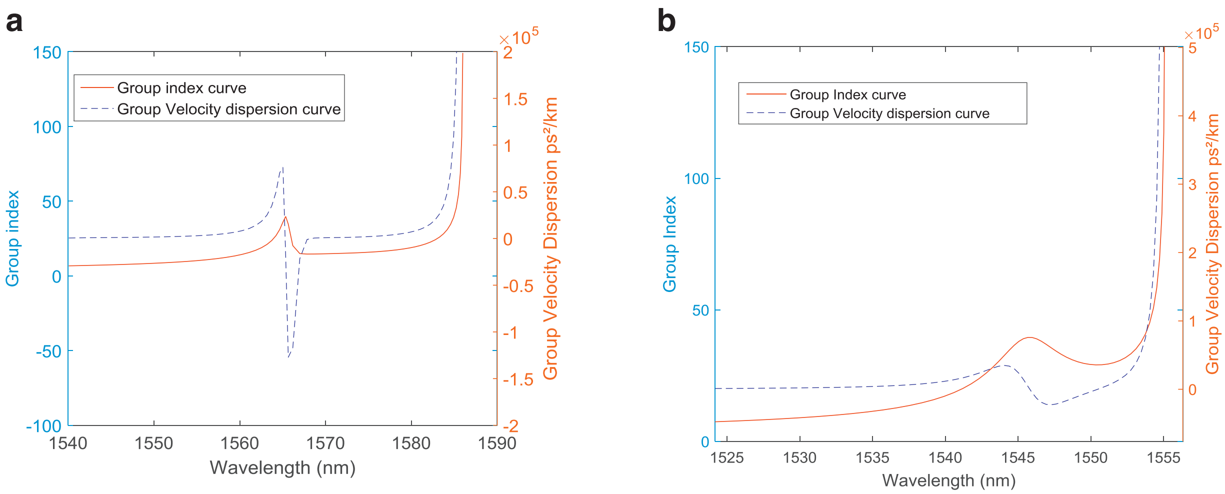

Fig. 11. (a) and (b) The group index curve and the corresponding GVD curve of the slow light modified PCW for $S = 0.325a$ and $S = 0.2775a$, respectively.

Table 1
Group index and bandwidth under different optimized shifting parameters.

Optimized shifting parameters		n_g	Bandwidth centered at 1550 nm (nm)
[16] Two-hole diameter variations		34	11
[17] Lateral hole position shifting		32	14.7
[23] Ring-shaped holes' structure		37	8
[24] Longitudinal hole position shifting		26	13.1
[25] Liquid infiltration of a slotted PCW		50	7.5
Current work	$S = 0.325a$	21	20.3
	$S = 0.3a$	20	15.6
	$S = 0.2775a$	35.5	9.3
	$S = 0.2625a$	65.5	5.3

4. Conclusion

In this paper, we have proved that a modified waveguide is capable of producing a wideband slow light with high group index and low group velocity dispersion, by only shifting the second rows of air holes adjacent to the center of the modified waveguide. Nearly constant group indices of 21, 20, 35.5 and 65 over 20.3 nm, 15.6 nm, 9.5 nm, 5.3 nm with low group velocity dispersion in the order of 10^5 ps^2/km have been achieved. Also, the operational wavelength can be tuned over a wide range span from 1544 to 1574 nm. The proposed design offers great potential for many applications, such as integrated circuits and sensors.

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