Wideband slow light in chirped slot photonic-crystal coupled waveguides

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Abstract: Wideband dispersion-free slow light in chirped-slot photonic-crystal coupled waveguides is proposed and theoretically investigated in detail. By systematically analyzing the dependence of band shape on various structure parameters, unique inflection points in the key photonic band with approximate zero group velocity can be obtained in an optimized slot photonic-crystal coupled waveguide. By simply chirping the widths of the photonic-crystal waveguides in the optimized structure, wideband (up to 20 nm) slow-light with optical confinement in the low dielectric slot is demonstrated numerically with relative temporal pulse-width spreading well below 8% as obtained from two-dimensional finite-difference time-domain simulations. The wideband slow-light operation of the proposed structures would offer significant potential for novel compact high-speed optical-signal-processing devices in silicon-based systems.

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References and Links


1. Introduction

Slow light [1–5] is a key technology now being heavily investigated for applications in optical modulators, optical regenerators, optical sensors, and various tunable delay devices. One of the most practical methods to realize slow light is based on photonic crystals (PC) [3–7]. Slow light in PC waveguides (PCW) offers compatibility with on-chip integration, room-temperature operation, and wide-bandwidth dispersion-free propagation [4,5]. Furthermore, the slow-light performance in PCW’s is not predetermined by the natural material dispersion [2]; the slow-light frequencies can be chosen by suitably designing the PCW. Thus, PCW’s are considered as one of the most promising methods to enhance light-matter interactions.

In PCW’s, however, light is typically strongly confined in the high-index guiding core, which is a drawback when an interaction with material outside the core is desired, such as for applications in silicon-based high-speed signal processing [9]. To achieve higher processing speeds, silicon needs to be combined with another high-nonlinearity material [9]. Silicon nanocrystals in silica is a typical nonlinear material that can be compatible with CMOS fabrication processes [10]. The low refractive index, typically only 1.65 in the material, however, renders light confinement difficult [11]. Slot waveguides [12,13] are novel photonic nanostructure that allow for the confinement and guiding of light in a low-index slot surrounded by higher-index materials. Owing to the advantage of the dielectric discontinuity at the interface between the high-index-contrast materials, slot waveguides have been shown to achieve up to a twentyfold field enhancement in the nanoscale low-index slot core compared with conventional strip waveguides [12]. Slot waveguides therefore offer an efficient method to confine light in the low-index zone and can be advantageously utilized in applications based on light emission, light modulation, and nonlinearities [14].

Obviously, it is very attractive to merge the benefits of both slow-light propagation in PCW’s and the dielectric discontinuity of slot waveguides. Recently, slot-based PCW’s have been theoretically proposed and experimentally demonstrated by several groups [8,11,15–20]. The waveguide modes of the slot PC-slab structures were first investigated to enhance light emission in silicon [15,16]. At roughly the same time, the dispersion properties of two-dimensional slot PC-slab waveguides were identified by measuring the waveguide transmittance [17], and a high group index of 150 was observed with losses comparable with that of state-of-the-art PCW’s [8]. By linearly tapering the slot width, light localization in slot PCW’s was also demonstrated [18]. Except for these two-dimensional PC structures, slow-light phenomena were also investigated in a preliminary optimized one-dimensional slot PC-coupled-resonator optical waveguide [11]. For practical applications, slot PCW’s were proposed and experimentally demonstrated in high-speed modulators [19,20]. Although great advances have been achieved, little attention [19] has been paid to the key issue of dispersion-free slow light in slot PCW’s. Actually, owing to large group-velocity dispersion and higher-order dispersion in the slow-light regime of the waveguide, a trade-off between the bandwidth and the effective group index of slow light [4,5] has to be made. Thus, in order to obtain practical devices, wideband dispersion-free slow light is an important consideration in slot PCW’s.

Currently there are mainly two groups of methods to implement dispersion-free slow light in PCW’s [5,19,21–30]. The first is associated with modifications of the structure parameters proximate to the waveguide core in a single line-defect PCW [19,21–24] to achieve a linear dispersion curve. The other is to use PC-coupled waveguides to obtain a flat band at an inflection point and then to shift it in a chirped structure [25–31]. In particular, the latter approach is reported to result in a broader bandwidth [5,25,27–29]. Ref [25], first theoretically reported the use of a chirped PCWs to implement wideband dispersion-free slow light. The dispersion and dispersion-compensation were investigated in detail. Subsequently, Ref [28] reported the first wideband dispersion-free slow-light experiment on chirped PCWs. Very recently, Ref [29]. used a folded chirped PCW to reduce the oscillations of the propagation spectra and to obtain a longer delay. A wide bandwidth and a very large tunable delay in this structure were demonstrated. However, because the dispersion-free slow-light mechanism in
the proposed structure is dispersion compensation [5,25,27–29], the pulse in the device is first dispersed and then recovered. Thus the pulse is not spatially compressed during the propagation, and so there is no peak-intensity enhancement in the device due to the slow light. In the present letter, the average group index in the proposed structure is increased, however, so the slow light will increase the interaction time between the light and material. Therefore, as the principle discussed in the Ref [4], the slow light in this device still will have a linear enhancement of phase velocity or effective index. Moreover, in this paper, slot waveguides are added in our chirped structures, providing the advantage of field confinement in the low dielectric zone. This, combined with the slow light propagation, provides opportunities for the use of active materials to overcome the disadvantage of the slow light in coupled waveguides [25,28,29]. Thus, the structure can provide a new opportunity for high-speed all-optical tunable-delay.

We first introduce the structure of the slot PC-coupled waveguide (SPCWG) and the operating principle to obtain wideband slow light. Next, band engineering of the device by using the plane-wave expansion method (PWE) [32] with equivalent index [33,34] of the slab is performed to find the ideal flat-band dispersion curve and as well as suitable structure parameters to introduce chirp. The results show that the ideal flat-band dispersion curve can be obtained by certain structure modulations, and the maximum slow-light bandwidth is limited by the multimode operation of the chirped SPCWG to about 30 nm. Following that, wideband (up to 20 nm) dispersion-free slow-light pulse propagation in several SPCWGs with average group index from 16.06 has been demonstrated by the finite-difference time-domain method (FDTD) [35]. Both wideband (up to 20 nm) dispersion-free slow-light propagation and field confinement in low dielectric zone are successfully demonstrated in the SPCWGs. These devices have potential for dense integration for large-scale high-speed data signal processing with low light power, such as applications in optics switching, optical sensors, optical regenerators, and tunable optical storage in silicon-based systems.

2. Structure and photonic band engineering of SPCWG

2.1 Structure and band engineering for ideal bands

A triangular lattice PC slab consisting of circular air holes (radii $R$) with lattice constant $a$ in a dielectric (silicon, $\varepsilon = 12$) background is assumed as the basic structure. As shown in Fig. 1(a), the center line of the circular holes in the perfect PC are modified to elliptical with major axis $R_{\text{long}}$ and minor axis $R_{\text{short}}$, and the two lines of circular holes next to the elliptical holes are deleted and substituted by two slots of width $W_{\text{slot}}$ that are filled with low-index material (silicon nanocrystals in silica, typical refractive index 1.65 [10]). In order to obtain the ideal flat-band shape with inflection-point slow-light modes as the center band shown in Fig. 1(b) [25–31], the size of circular holes (radii $R_{\text{outside}}$) just outside the slots are also modified with respect to $R$. The choice of the elliptical central holes is based on the previous investigations of PCWs [25–31], in which three lines of holes at the center separating the two coupled waveguides were employed. The radius of the center-line holes is enlarged to reduce the refractive index, and the position of the holes beside the waveguides is shifted towards the center of the structure. Modifications of the elliptical shape of the single central holes can mimic a similar index modification as their modifications of three lines of holes. The ideal photonic band consist a center flat band line and which is sandwiched between negative and positive dispersion on the higher and lower frequency side, respectively. To obtain perfectly dispersion-free slow light, the opposite dispersion should be perfectly symmetric with the flat band. When suitable structure parameters are chosen, such an ideal band can be shifted up or down, while the ideal shape is maintained. If such modifications are continually made (i.e., chirp) along the axis of a structure, a light pulse is first affected by the dispersion but upon propagation is subsequently recovered due to dispersion of the opposite sign, and different frequencies are delayed at different positions along the structure [25,27–29]. Accordingly, the bandwidth and average group index are controlled by the range and slope of the chirp. Thus, through chirping the optimized structure, wideband dispersion-free slow light can be obtained.
Fig. 1. (a) Schematic diagram of the SPCWG; black denotes silicon, white denotes air, and gray denotes silicon nanocrystal in silica. The major and minor axes ($R_{\text{long}}$ and $R_{\text{short}}$) of the elliptical air holes, the radii ($R_{\text{outside}}$) of two lines of holes in vicinity of the slots, the width ($W_{\text{slot}}$) of the slot, and the distance ($d_y$) between the center of the elliptical holes and the center of the holes nearby the slots are set to be optimized. (b) Band structure of the optimized SPCWG calculated by FDTD [30]; only the even mode in the electric-field component $E_y$ (quasi-even in $z$ direction and odd in $y$ direction) is considered. The band in the center of the figure is of chair shape with an inflection point with approximate zero group velocity. The single bands composed of differently colored dots are a conventional result of the band structure calculated using Meep [35]. The parameters are $R = 0.3a$, $R_{\text{outside}} = 0.45a$, $R_{\text{long}} = 0.76a$, $W_{\text{slot}} = 0.4a$, $R_{\text{outside}} = 0.2a$, $d_y = 0.85 \times 1.732a$. The triangle-shaped dots with gray denote modes of the structure. The rectangular shadow zone indicates that the normalized frequency range can be used to chirp.

A key point is to form the ideal band shape by choosing the suitable chirp. Thus, it is very important to understand the relationship between modulation of the structural parameters of the SPCWG and the effect on the photonic bands. The structure parameters of the SPCWG shown in Fig. 1(a) are modified to change the optical properties. Because the full three-dimensional calculation of the band frequency is very time consuming, a two-dimensional analysis with a slab equivalent index of 2.9 is adopted [33], which is expected to be sufficiently accurate to estimate the group velocity in the slow-light regime. The effective index method [33] is quite accurate even for complex bands calculations in PC slabs and the calculation error here is evaluated to be $< 3\%$. It is known that the theoretical properties of PC-slab devices [34] designed by the same method agree well with the experimental results. Thus, in this paper, we will also use the effective-index approximation to simplify the calculation. By considering the trade-off between fabrication technology and the obtained width of photonic band gap, the hole radius of the background PC is chosen with a popular value $R = 0.3a$. This gives a photonic band-gap range from normalized frequency 0.2468 to 0.3153 for the transverse-electric (TE)-like mode (electric fields are mostly in the plane) according to the PWE [32] calculation.
Fig. 2. Main TE photonic band as a function of various parameters. (a) Dependence of the main band on $R_{\text{short}}$ in the SPCWG, the parameters are with $R = 0.3a$, $R_{\text{long}} = a$, $R_{\text{outside}} = 0.2a$, $W_{\text{slot}} = 0.2a$, $d_y = 1.732a$. While $R_{\text{short}}$ is increased from 0.2a to 0.7a with a step 0.05a, the waveguide band is shifted up accordingly. The ideal chair shape is formed at approximately $R_{\text{short}} = 0.45a$. (b) Dependence of the main band on $R_{\text{long}}$ in SPCWG, the parameters are with $R = 0.3a$, $R_{\text{short}} = 0.45a$, $R_{\text{outside}} = 0.2a$, $W_{\text{slot}} = 0.2a$, $d_y = 1.732a$. While $R_{\text{long}}$ is increased from 0.5a to 1.2a with a step 0.05a, the waveguide band is shifted up accordingly. The ideal chair shape is formed at around $R_{\text{long}} = a$. (c) Dependence of the main band on $R_{\text{outside}}$ in the SPCWG, the parameters are with $R = 0.3a$, $R_{\text{short}} = 0.45a$, $R_{\text{long}} = 1a$, $W_{\text{slot}} = 0.2a$, $d_y = 1.732a$. While $R_{\text{outside}}$ is increased from 0.1a to 0.45a with a step 0.05a, the waveguide band is shifted up accordingly. The ideal chair shape is formed at approximately $R_{\text{outside}} = 0.2a$.

In Figs. 2 and 3, we present the dependence of the main TE photonic band (quasi-even in $z$ direction and odd in $y$ direction, which can only be excited by the fundamental mode of the dielectric waveguide) and the various structure parameters calculated by the PWE method [32]. Figures 2(a), 2(b), and 2(c) give the results for various values of $R_{\text{short}}$, $R_{\text{long}}$, and $R_{\text{outside}}$, respectively; Figs. 3(a) and 3(b) show the dependence of the band on $d_y$ and $W_{\text{slot}}$, respectively. The structure-parameter dependences in Figs. 2 and 3 are classified according to their effects on the changes of dispersion curves. Figure 2(a) illustrates the shifting tendency of the photonic bands when the $R_{\text{short}}$ is gradually changed from 0.2a to 0.7a with a step 0.05a. When $R_{\text{short}}$ is increased, the slope of the band gradually increases from negative to positive in the region wave vector range $0.36<\kappa<0.4$. The slope is zero with $R_{\text{short}}=0.45a$, where we observe the inflection points have approximately zero group velocity. Similarly, Fig. 2(b) shows the variation of the band when we adjust the length of the major axis $R_{\text{long}}$ of the elliptical holes. When $R_{\text{long}}$ is increasing, the band undergoes changes similar to those in Fig. 2(a); however, we note that the change in slope is less sensitive in Fig. 2(b) than that in Fig. 2(a). We can obtain a nearly zero slope at $R_{\text{long}}=a$; however, as shown in Fig. 2(c) the slope of the band is influenced most by tuning of $R_{\text{outside}}$. From Fig. 2, we can see that the main band is very sensitive to the parameters of the holes next to the slots. Varying each parameter can strongly modify the dispersion curve; thus, these parameters must be chosen...
carefully. In contrast, as shown in Fig. 3, the shapes of the main band are only weakly dependent on $d_y$ and $W_{\text{slot}}$. In these cases, while the effective index may be changed only slightly by varying $d_y$ and $W_{\text{slot}}$, the band may be shifted along the vertical frequency axis. Consequently, these two parameters, viz. $d_y$ and $W_{\text{slot}}$, are more suitable to be used as the chirp parameters. Specifically, for our study we note that the normalized frequency of the zero group-velocity portion of the band is less sensitive to $W_{\text{slot}}$ than to $d_y$; therefore, we choose $d_y$ as the chirp parameter in the sequel.

Here, we give some explanation of the phenomena shown in Figs. 2 and 3. In general, the modes of PCW’s can be categorized as either index-guided or gap-guided [36]. The light in the waveguide core tends to be more influenced by index guiding and the light in position that is deeper into the surrounding PC zone tends to be more influenced by gap guiding. An anticrossing between guiding mechanisms of these two types determines the local shape of the dispersion curve of the band of interest. Focusing on $R_{\text{outside}}$, because the outside holes play an important role in both index- and gap-guided modes [21–23], varying the size of these holes can change the intrinsic interplay of the index- and gap-guiding mechanisms. Thus, the band of interest is highly sensitive to $R_{\text{outside}}$. Consequently, $R_{\text{outside}}$ can be conveniently used to tune the dispersion curve to obtain a flat-band slow-light region. The situation becomes complex for the case of elliptical holes since they lie between the two slots. The elliptical holes can be regarded as either the waveguide core or the waveguide border. If we regard the two slots as two waveguides, the elliptical holes can be seen as the waveguide border. On the other side, we can also regard the ellipses, slots, and the outside holes together form a PC multimode defect waveguide. As a result, the ellipses can also be seen as the core of the new waveguide. Thus, $R_{\text{short}}$ and $R_{\text{long}}$ have a relatively lower impact on the dispersion curve. We now use the concept of effective refractive index to understand the difference between the effects of $R_{\text{short}}$ and $R_{\text{long}}$. When the effective refractive index decreases, the dispersion curves shift toward higher frequency. Varying $R_{\text{short}}$ with the same value as varying $R_{\text{long}}$ will produce a larger change of the volume of high-index material between the slots for $R_{\text{long}}$ is usually larger than $R_{\text{short}}$. Consequently, $R_{\text{short}}$ has greater influence on the effective index variation than $R_{\text{long}}$. Accordingly, the dispersion curve is more sensitive to $R_{\text{short}}$ than $R_{\text{long}}$. Similarly, we can understand the dispersion curves variation in Fig. 3.

Combining the effects of varying the structural parameters shown in Figs. 2 and 3, a relatively ideal chair shape can be obtained as shown in Fig. 4. In practice, one can scarcely obtain a perfect chair-shaped band. We only can approximate the ideal. Thus, as a preliminary optimized result, we took the curve shown in Fig. 4 as a relatively ideal chair-shaped band.

![Fig. 3. (a) Dependence of the main mode on $d_y$ in the SPCWG, the parameters are with $R = 0.3a$, $R_{\text{short}} = 0.45a$, $R_{\text{long}} = a$, $R_{\text{outside}} = 0.2a$, $W_{\text{slot}} = 0.2a$ and $d_y$ is varied. While $d_y$ is increased from $0.85 \times 1.732a$ to $1.15 \times 1.732a$ with a step $0.025 \times 1.732a$, the main band is shifted down accordingly and the ideal chair shape is almost maintained. (b) Dependence of the main mode on $W_{\text{slot}}$ in SPCWG, the parameters are with $R = 0.3a$, $R_{\text{short}} = 0.45a$, $R_{\text{long}} = a$, $R_{\text{outside}} = 0.2a$, $d_y = 1.732a$. While $W_{\text{slot}}$ is increased from 0 to $0.5a$ with a step $0.05a$, the main band is shifted up accordingly and the ideal chair shape is little changed.](image-url)
Unfortunately, however, the ideal flat-band dispersion curve is very close to a higher band, which overlaps within some frequency range the band of interest, in turn potentially leading to multimode operation. Furthermore, these two bands have the same mode field symmetry. Therefore, the bandwidth for single mode slow light is limited to the range between the normalized frequency at which zero group velocity occurs in the ideal chair-shaped dispersion curve and the lowest normalized frequency in the upper band as indicated by the thin shaded horizontal band shown in Fig. 4. The bandwidth-to-midband ratio defined as $\Delta \omega / \omega$—a typical figure of merit—is calculated to be only 0.8293% for this situation. In practice, the maximum bandwidth consists of two parts separated by the flat band frequency. The upper part is right the bottom half of the labeled shadow zone, the bottom part exists below the flat band. For the sum of the two parts are equal to the whole width of the labeled shadow zone, for simplicity, we chose to shadow only the upper side of the flat band as the maximum bandwidth.

Fig. 4. Preliminary optimized band structure of the SPCWG. The parameters are $R = 0.3a$, $R_{long} = a$, $R_{short} = 0.45a$, $R_{outside} = 0.2a$, $W_{slot} = 0.2a$, and $d_y = 1.732a$. The normalized bandwidth is 0.8293%. The rectangular shadow zone indicates the single-mode normalized frequency range which can be used to chirp.

2.2 Extension of the single mode bandwidth

As discussed above, the slow-light bandwidth is limited to the single-mode frequency range. Therefore, methods are needed to extend the bandwidth. As shown in Figs. 2 and 3, the shape of the ideal band is very sensitive to the parameters $R_{short}$, $R_{long}$, and $R_{outside}$. Accordingly, on the one hand, variation of these parameters would cause the band shape to deviate from the ideal, and thus they are not suitable to be tailored. On the other hand, the ideal band shapes are maintained for various $d_y$ and $W_{slot}$. They are consequently suitable to be used as the tuning parameters.

To extend the bandwidth, the tendency of the $\Delta \omega / \omega$ on the change the $W_{slot}$ and $d_y$ should be investigated. Figures 5(a) and 5(b) exhibit the $\Delta \omega / \omega$ dependence on $d_y$ and $W_{slot}$, respectively. In the calculation, $d_y$ and $W_{slot}$ are varied, while the other parameters were held constant as in Fig. 4. As shown in Fig. 5(a), while $d_y$ is increased from 0.85 $\times$ 1.732$a$ to 1.15 $\times$ 1.732$a$, the bandwidth is narrowed. Thus, in practice, the value of $d_y$ should be kept as small as is allowed by the fabrication technology. In Fig. 5(b), while $W_{slot}$ is increased from 0 to 0.5$a$, the bandwidth is first narrowed and then extended. Varying $W_{slot}$ can obtain a larger bandwidth than by varying $d_y$. Therefore, $W_{slot}$ is more suitable to be used to extend the single-mode bandwidth. At the same time, $d_y$ is more suitable to be used as the chirp parameter to extend the slow-light bandwidth. In practice, there are also two limitations for choosing of $W_{slot}$ First, for the slot waveguides, to maintain high optical confinement in the slot zone, the width of the slot waveguide is required to be no greater than the characteristic decay length inside the slot. Second is the limitation of the fabrication technology. When we increase the width of the slot, we also make one interface of the slot close to the first rows of
holes, and the other interface close to the center row of holes. In view of limitations imposed by the fabrication technology, a minimum line width is required. A final optimized band structure is shown in Fig. 1(b). In the figure, FDTD with a high resolution of 64 grids per period is adopted to calculate the band structure to validate the previous PWE analysis. While almost the same ideal band shape is obtained, a larger bandwidth-to-midband ratio $\Delta\omega/\omega = 1.95332\%$ results, which will result a bandwidth of about 30 nm centered at 1550 nm.

![Figure 5](image)

**Fig. 5.** (a) $\Delta\omega/\omega$ dependence on the structure parameter $d_y$. As $d_y$ is increased, the normalized bandwidth decreases. (b) $\Delta\omega/\omega$ dependence on $W_{slot}$. As $W_{slot}$ is increased, the normalized bandwidth first decreases and then increases. The normalized bandwidth that can be obtained by varying $W_{slot}$ is larger than that by varying $d_y$.

3. Pulse propagation in the chirped SPCWG

When such an ideal band in Fig. 1(b) is shifted in a chirped structure [see Fig. 6(a)], a light pulse propagating from left to right is first affected by the initial dispersion but is subsequently recovered by dispersion of the opposite sign, with the various frequencies within the pulse bandwidth delayed at different positions in the chirped structure [25,27–29]. Therefore, wideband dispersion-free slow light can be obtained. The bandwidth and average group index are controlled by the range and slope of the chirping. Thus, how to chirp the optimized structure to obtain wideband slow light needs to be considered. Figure 6(b) shows the dependence of the flat-band slow-light frequency on chirping $d_y$. As shown in Fig. 6(b), a linear dependence of the normalized frequency of the flat-band region is obtained. It is therefore quite convenient to choose the chirp range to achieve the desired bandwidth. Specifically, chirping $d_y$ from $0.825 \times 1.732a$ to $0.875 \times 1.732a$ will obtain a wide bandwidth from normalized frequency $0.3023(2\pi c/a)$ to $0.2959(2\pi c/a)$, corresponding to $\Delta\omega/\omega = 2.1397\%$. This result is larger than the previous analyzed single-mode bandwidth limit, and thus it is not necessary to further consider the chirp range.

Based on the foregoing design principles, we investigate pulse propagation through this chirped structure by FDTD [35]. In order to distinguish the chirped structure, a high resolution of 64 grids per period is adopted. Increasing the chirp range requires a longer device length, which may lead to computations that are too numerically expensive. We therefore only chirp $d_y$ from $0.835 \times 1.732a$ to $0.865 \times 1.732a$ which will obtain slow light with a bandwidth of $0.0038(2\pi c/a)$. As shown in Fig. 7, the chirped SPCWG has $R = 0.3a$, $R_{short} = 0.45a$, $R_{long} = 0.76a$, $W_{slot} = 0.4a$, $R_{outside} = 0.2a$, and $d_y$ is chirped from $0.835 \times 1.732a$ to $0.865 \times 1.732a$ in a length of $150a$, which are chosen according to the previous analysis. Two strip waveguides with width of $3.835 \times 1.732a$ and $3.865 \times 1.732a$ are added at the left and right sides of the chirped SPCWG, respectively, to couple light into and out the structure. Perfectly matched absorbing boundary layers are applied to the surroundings of the structure. A Gaussian pulse source centered at $0.2992(2\pi c/a)$ with a frequency width $\Delta\omega = 0.0038(2\pi c/a)$ is then injected at the input port, which corresponds to a bandwidth nearly 20 nm centered at 1550 nm for a PC lattice constant of 465 nm. From the optimized band structure shown in Fig. 1(b), this
frequency band range corresponds to a normalized wave vector range from 0.3287 to 0.39735. Thus, a group index of 18.1 calculated from \( c \Delta k/\Delta \omega \) [25] is expected to be obtained from this chirped structure. As shown in Fig. 7, four monitors are added at the positions \( a, 5a, 155a, 159a \) respectively in the propagation direction to detect the flux in time.

![Fig. 6](image_url)

**Fig. 6.** (a) Schematic diagram of the SPCWG including chirping of \( d_y \); black denotes silicon, white denotes air and gray denotes silicon nanocrystal in silica. (b) Dependence of the flat-band slow-light normalized frequency on \( d_y \).

![Fig. 7](image_url)

**Fig. 7.** Structure of the chirped SPCWG. Black denotes silicon, white denotes air, and gray denotes silicon nanocrystals in silica. The four red lines denote the four monitors numbered one to four, respectively. Surrounding the structure is a perfectly matched layer.

Figure 8 shows the time-dependent flux associated with the pulses corresponding to the time step propagation through the monitors. The output pulse shapes are almost maintained the same as the input pulses. As shown in Fig. 8(a), the full width at half maximum (FWHM) of the incident optical pulse detected by monitor one is \( 435a/c (~0.674 \text{ ps}) \); while that of the output pulse detected by monitor four is \( 468a/c (~0.725 \text{ ps}) \). The relative pulse shape expansion is 7.586%. Correspondingly in Fig. 8(b), the FWHM of the incident optical pulse detected by monitor two is \( 439a/c (~0.681 \text{ ps}) \); while that of the output pulse detected by monitor three is \( 472a/c (~0.732 \text{ ps}) \). The relative pulse shape expansion is 7.52%. The temporal stretches of pulses at the output port are due mainly to the shape deviation of the ideal band shape as \( d_y \) is varied in the chirped SPCWG. The total delay between the two peaks in Fig. 8(a) is \( ~2444a/c (~3.788 \text{ ps}) \) and that of in Fig. 8(b) is \( ~2410a/c (~3.736 \text{ ps}) \). Thus using the time-of-flight method [37], the average group index in the chirped SPCWG can be calculated with 16.067 and that in the input and output strip waveguides is 4.25. Therefore, slow light with wide bandwidth is observed in the SPCWG section, which is in reasonable agreement with that predicted from the band structure. From Fig. 8, we also notice that the envelopes of the pulse shapes at monitor 3 and 4 are almost the same. Quite interesting is that the pulse monitor 3 exhibits higher bottom envelope than monitor 4, because of the reflection
from the end of the structure. Monitor 3 is located near the interface of the PCW and the strip waveguide producing a large reflection at the monitor. Thus, the pulse as detected by monitor 3 has a higher bottom to the envelope. Another difference is that the maximum peak at monitor 3 is a little less than that at monitor 4. That is because of the slow light operation in PCW; some fields extend to the border of the PC zone that the monitor cannot detect. However, the light field in the strip waveguide is barely extends to monitor 4. Therefore, the maximum as seen by monitor 3 is lower than that at monitor 4.

Fig. 8. Temporal pulse shapes detected by the monitors in the chirped SPCWG. The pulses are normalized to the maximum of the peak detected by monitor one (a) Temporal pulse shapes detected by monitor one and monitor four positioned at the input and the output of the whole structure respectively. (b) Pulse shapes detected by monitor two and monitor three positioned at the input and the output of the chirped SPCWG.

Fig. 9. Temporal pulse shapes detected by the monitors in the unchirped structure, the fluxes are normalized to the maximum of the peak detected by monitor one. (a) Pulse shapes at the input and the output of the entire structure. (b) Pulse shapes at the input and the output of the SPCWG.

By conducting simulations with the same Gaussian pulse source, light propagation in a structure with no chirp is also investigated. In this case, all the parameters are maintained the same as the chirped SPCWG except the structure parameter $d_i = 0.85 \times 1.732a$ is set constant. Figure 9 shows the time-dependent flux associated with the pulse corresponding to the time step propagation through the monitors in this case. As shown in Figs. 9(a) and 9(b), while one pulse shape is observed at the input part detected by monitor one and monitor two respectively, almost four pulses are observed at the output of the structure detected by monitor three and monitor four, respectively. Due to the great dispersion of the SPCWG, the signal is distorted greatly. In this uniform structure, as the band structure shown in Fig. 1(b) indicates,
the slopes of the ideal band around the zero group velocity are extremely varied. Thus, when a wideband pulse is injected into the structure, different frequencies have different phase velocities leading to pulse breakup at the output port. Comparing Figs. 8 and 9, we conclude that wideband signals can be transmitted with a slow group velocity and little dispersion in the chirped SPCWG by varying $d$; in the absence of the chirp, the pulse shape is severely distorted.

We next turn our attention to the electric-field localization in the slot. Figure 10(a) shows a snapshot of $E_y$ at time step $2500a/c$ (about 3.875 ps) obtained from previous simulations of the chirped structure. As expected, a symmetric field distribution is observed. We see that $E_y$ is confined mainly in the slot and the holes nearby the slot, which can be explained by the dielectric discontinuity. The $E_y^2$ profile at the section of 80.5$a$ at the same time is plotted in Fig. 10(b), clearly illustrating the electric-field confinement in the low-index region in the slot.

![Fig. 10. (a) $E_y$, time step 2500a/c (about 3.875 ps) with temporal Gaussian-pulse input. (b) $E_y^2$ profile of the beam at the position of 80.5a.](image)

However, as shown by the colors in Fig. 10(a), the field amplitude along the first row of holes is also strong. The reason is that, the slow light in the guided modes within the PCW are mainly band-gap-guided [36]. In addition, the fields of the band-gap-guided modes usually extend from the waveguide core into the PC border. That is why the first several rows of holes strongly impact the group index and the field distribution [21–24]. Let us focus on the first rows of holes, one side of the rows is PC zones; the other side is the air slots. The holes in these rows are modified and the propagating light field extends into these rows. The extended lights are modulated and the fields are locally enhancement in these holes. The observation of this phenomenon is very interesting; it gives us a direction to improve our structure. It is difficult to fabricate a device in which nonlinear material is filled only within the slots and not in the surrounding holes. That is one of the disadvantages of our design. Therefore, our structure is preferred compared with the structure of Ref [38], in which all the holes are filled with silica.

On the other hand, adding the slots to the structure did demonstrate light confinement in the low dielectric zone. To prove that, we used the PWE method calculating the modal field for both the structure with slots and the structure without slots. Thus, the influence of the additional slots would be distinguished. The PWE method only supports periodic structure; thus only unchirped structures can be investigated. Figure 11 shows the $E_y$ modal fields of the waveguides with and without slots at the wave vectors near and at the flat band. From the figures, we see that the field confinement in the low-index slot zone can be implemented. There is large field enhancement in the waveguide zones in both the structures with and without the slots. Thus, employing the slots can make good use of that the large fields in the low-index material. However, for the zones which around of the slots, especially for the first and center rows of holes, the intensities are also strong. This suggests that we do not have to only fill the slot with the low-index material. All the holes can also be filled, so that the modal field will be better used. Thus, the properties of the low dielectric can be combined within the PCW structure like Ref [38].
Fig. 11. $E_y$ modal field for the PCW without (upper three) and with (bottom three) the slots for three different wave vectors in the negative-dispersion zone, flat-band zone, and positive-dispersion zone respectively. The structure parameters with slots are just the same as those in Fig. 1(b); and the parameters in the upper conventional PCW are also the same, but without the slots. Both the structures have a similar chair-shaped band, and their bandwidths for slow light are indicated in Fig. 5(b).

Table 1. Pulse propagation with various chirp ranges of $d_y$.

<table>
<thead>
<tr>
<th>Chirp range of $d_y \times 1.732a$</th>
<th>Bandwidth for center wavelength 1550nm nm</th>
<th>Average Group index</th>
<th>Group index bandwidth product</th>
<th>Relative pulse shape expansion at Monitor 3 compared with Monitor 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.835 to 0.865</td>
<td>19.7</td>
<td>16.06</td>
<td>316.38</td>
<td>7.52%</td>
</tr>
<tr>
<td>0.84 to 0.86</td>
<td>13.1</td>
<td>20.3</td>
<td>265.93</td>
<td>6.02%</td>
</tr>
<tr>
<td>0.845 to 0.855</td>
<td>6.5</td>
<td>29.1</td>
<td>189.15</td>
<td>5.15%</td>
</tr>
<tr>
<td>0.8475 to 0.8525</td>
<td>3.26</td>
<td>40.23</td>
<td>131.15</td>
<td>5.24%</td>
</tr>
<tr>
<td>0.849 to 0.851</td>
<td>1.3</td>
<td>48.5</td>
<td>63.05</td>
<td>5.15%</td>
</tr>
</tbody>
</table>

Pulse propagation assuming other chirp ranges of $d_y$ are demonstrated with a small relative pulse shape expansion of monitor 3 to monitor 2 less than 8%, as shown in Table 1. If we chirp $d_y$ within a narrower range from 0.84 × 1.732a to 0.86 × 1.732a over a SPCWG of the same length, a higher average group index of 20.3 with a narrower bandwidth of about 13.1 nm can be obtained. In the same length, further reduce the chirp range of $d_y$, such as chirping $d_y$ from 0.845 × 1.732a to 0.855 × 1.732a, from 0.8475 × 1.732a to 0.8525 × 1.732a, and from 0.849 × 1.732a to 0.851 × 1.732a, a higher average group index of 29.1, 40.23, and 48.5 but with a narrower bandwidth of about 6.5nm, 3.26nm, and 1.3nm are obtained, respectively. By further decreased the chirp range of $d_y$, even higher group index and narrower bandwidth would be obtained. In principle, the delay and bandwidth issue still constrains the slow light in the chirped structure. As we can see in Table 1, the group-index-bandwidth product is reduced while the average group index is increased, the wider bandwidth proportionally reduces the average group index, which is averaged by the chirp, and a smaller slope ($\Delta d_y/L$) of the chirp leads to a larger average group index but with a narrower bandwidth [25]. During our simulations, in the same device length, if the chirp range is chosen with a smaller value, a smaller peak transmittance will be observed. That is because a smaller chirp range will result a larger average group index, and will cause internal resonances [29]. Therefore the loss will be increased when a smaller chirp range is used. To overcome the problem, a folded chirp structure [29] was proposed, and demonstrated to have a better performance. We can also use a similar folded chirp structure to obtain low propagation loss and relative high average group index.

4. Conclusion

In conclusion, wideband slow light in chirped SPCWG is proposed and theoretically investigated in detail. Design principles to obtain the ideal chair shape of the dispersion curve as well as the effects of chirping various parameters are discussed. Light propagation with wide bandwidth up to 20 nm for center wavelength 1550nm but small average group index of 16 and high average group index of 48.5 but narrow bandwidth of 1.3 nm are demonstrated in the proposed structure with little dispersion by the FDTD simulations. Broader bandwidth up to 30 nm but with smaller average group index than 16 and higher average group index than 48.5 but with bandwidth narrower than 1.3 nm can also be expected in the proposed structure.
These values exceed those of other reported structure [19]. Considering that chirping only the structure parameter $d_y$ can lead to wideband slow light, the structure is more convenient to fabricate and design. Both the merit of light confinement in a low-index slot waveguides and the slow-light propagation are identified in this structure. Therefore, external control of the chirp would be expected and tunable devices are possible. This structure has the potential for various applications, such as wideband slow-light systems, optical buffer memories, efficient optical switches, data synchronizers, integrated optical filters, wavelength-division multiplexing, dispersion compensation, optical regenerators and nonlinear devices for densely integration, and large scale high speed data signal processing in silicon based systems.

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