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Flat broadband slow light with low dispersion in coupled resonator optical waveguide based on one-dimensional photonic crystals*

LI Chang-hong (李长红)[1], WAN Yong (万勇)[2], and YU Rui-tao (于瑞涛)[1]**

1. College of Automation Engineering, Qingdao University, Qingdao 266071, China

2. College of Physics Science, Qingdao University, Qingdao 266071, China

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By introducing multiple defect layers in one dimensional (1D) photonic crystal (PC), the broadband slow light with low dispersion is obtained. The slow light pass band is smoothed by adjusting the spacing and the number of cavities. In the optimized structure, the bandwidth is 8.556 1 nm with flatness below $8.805\,2\times10^{-4}$, the group velocity is in the range from 0.029*c* to 0.042 4*c*, and the group velocity dispersion (GVD) parameter *D* is in the range from -14.410 3 ps/(mm·nm) to 15.124 ps/(mm·nm). Moreover, by material optimization, the slow light properties can be improved further. With suitable materials, the slow light pass band can be broadened to 20.057 8 nm with flatness of 5.4×10^{-3}, and the GVD parameter *D* decreases to the range from -4.657 8 ps/(mm·nm) to 4.790 4 ps/(mm·nm).

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Slow light is a key technology in optical buffering, time-domain processing of optical signals, optical logic and switch for the next-generation photonic network traffic[1-5]. It also offers the possibility for spatial compression of optical energy and the enhancement of linear and nonlinear optical effects[6]. As an artificial nanostructure, photonic crystal (PC) is one of the most promising methods to generate slow light with more advantages than others[7-9]. Unfortunately, PC slow light encounters issues of the narrow delay-bandwidth and large group velocity dispersion (GVD).

In order to eliminate this distortion and maintain broadband slow light with high group index n_g, many researches have been done[10-19]. Most of these researches mainly focus on two dimensional (2D) slow light PC structure. One dimensional (1D) PC, as the simplest structure, is easy to be fabricated and has also been proposed to realize slow light[20]. However, most of 1D PC slow light researches mainly focus on the band edge slow light[9,21], which usually suffers from large GVD, and causes strong signal distortion[22]. Recently, using dispersion compensation principle, by introducing circular holes or grating waveguide into the 1D grating, flat band slow light with a wide bandwidth has also been reported[23,24]. But in these two methods, holes have to be introduced into the center of the 1D grating waveguide, which increases the complexity of design and fabrication process.

In 1D PC structure, the ultra low group velocity exists at the photonic band gap (PBG) edge and defect mode, but the slow light bandwidth is too small to be utilized for practical devices. Inspired by the slow light transmission in coupled resonator optical waveguide (CROW)[25,26], which is achieved through weak coupling between adjacent localized high-*Q* cavities mode, we design CROW by inserting multiple defect layers as micro-cavities into 1D perfect PC structure to broaden the slow light band and reduce the GVD. The dependences of slow light properties on the cavities spacing and number are investigated. To further improve the slow light properties, the refractive index effects of fundamental layer and cavity layer are discussed.

The structure of 1D PC CROW can be depicted as $\mathrm{M_{end}/C/M_{in}/C/M_{in}\cdots/C/M_{end}}$, where C means the half-wavelength defect layer as micro-cavity, and $\mathrm{M_{end}}$ and $\mathrm{M_{in}}$ denote the quarter-wave stack with high and low refractive index dielectric layers alternatively at the end of structure and micro-cavities spacing within the CROW, respectively. $\mathrm{M_{end}}$ and $\mathrm{M_{in}}$ are formed as $\mathrm{(AB)}^N\mathrm{A}$ and $\mathrm{(AB)}^M\mathrm{A}$, where A and B mean the high and low refractive index layers, respectively, and *N* and *M* are the numbers of fundamental periods (AB). Fig.1 shows the basic structure of 1D PC CROW, where we set N=2, M=4, and the number of cavities is 7. In our simulation, the refractive indices of A and B are 2.8 and 1.5, respectively. The material of cavity layer is the same as that of B layer.

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** E-mail: jiluch@126.com

The compared single defect 1D PC structure can be depicted as $(BA)^6C(AB)^6$, and the simulation results are obtained by transfer matrix method (TMM)[27].

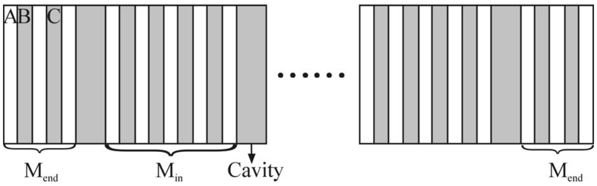


Fig.1 Schematic diagram of 1D PC CROW used in the simulation

Fig.2 shows transmission spectrum, group velocity v_g and GVD parameter D as a function of wavelength for 1D PC CROW and 1D PC with single defect. The transmission spectra of the pass band in PBG are shown in Fig.2(a). It is found that seven transmission peaks appear in the pass band of spectrum of CROW. The number of peaks is in accordance with the number of cavities. The bandwidth of pass band is $\Delta\lambda$=37.9 nm (1 531.3–1 569.2 nm). The full width half maximum (FWHM) of transmission peak of single defect structure is 0.8 nm (1 549.6–1 550.4). Compared with that of single defect 1D PC structure, the transmission band of CROW is broadened by 47.375 times. However, although the band is broadened, the transmission band is uneven because of the appearance of multiple peaks. It should be smoothed.

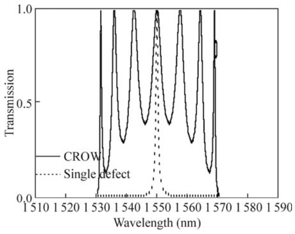
The group velocity of transmission spectrum can be evaluated as $v_g = d\omega/dk = c/n_g$, where ω is the angle frequency of incident light, k is the wavevector in the propagation direction, and n_g is the group index, which can be depicted as[28]

$$n_g(\omega) = c\frac{dk}{d\omega} = n_{eff} + \omega\frac{dn_{eff}}{d\omega}, \tag{1}$$

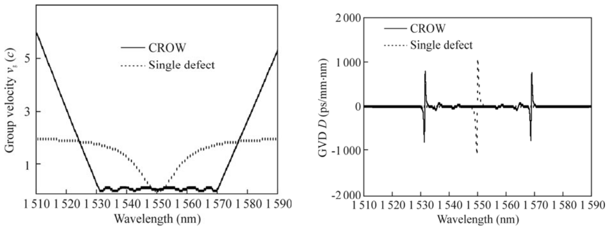
where n_{eff} is the effective index of 1D PC structure. The GVD parameter D is given as[29]

$$D = \frac{d}{d\lambda}(\frac{1}{v_g}) = \frac{1}{c}\frac{dn_g}{d\lambda}. \tag{2}$$

The group velocity v_g and GVD parameter D are plotted as a function of wavelength in Fig.2(b) and (c). It is found that in the pass band of CROW, the group velocity is in the range of 0.010 5c–0.182 1c. While for single defect PC, the group velocity has a minimum of 0.005 3c, the transmission peak is very narrow with 0.8 nm, and correspondingly, the GVD parameter D is changed sharply from -982.077 ps/(mm·nm) to 981.5 ps/(mm·nm). In the pass band of CROW, at band edge the parameter D sharply changes from -743.87 ps/(mm·nm) to 740.66 ps/(mm·nm). However, it is around the zero dispersion point in the range from -65.837 to 63.407 within the pass band. Furthermore, the closer to the pass band center, the smaller the GVD parameter D is. Fig.2(c) shows that there is a flat region with small GVD in the slow light region of pass band. This simulation results indicate that the introduction of multiple cavities makes pass band broaden effectively and maintain very low group velocity. Simultaneously, the GVD maintains a relatively small value. On the other hand, the pass band needs to be flattened.



(a) Transmission spectra of the pass band in the PBG



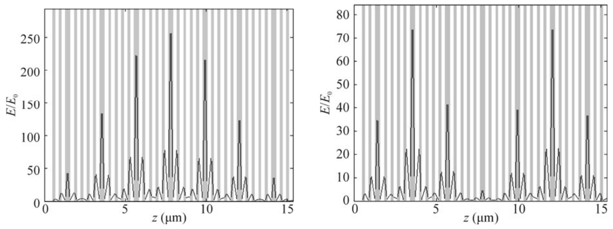
(b) The group velocities of the transmission band

(c) GVD parameter D of the pass band

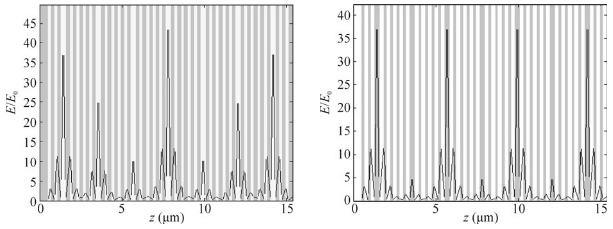
Fig.2 Transmission properties of 1D PC CROW with multiple cavities and 1D PC with single defect

In order to demonstrate the broadband slow light transmission in 1D PC structure, we investigate the electric field distribution in 1D PC CROW[30,31]. Fig.3 illustrates the electric field distribution of seven peak wavelengths shown in Fig.2(a) in 1D PC CROW. It shows that the energy is mainly confined in defect cavities, and the fields of different wavelengths are confined in different cavities. Furthermore, the simulation demonstrates that the electric field distributions of the symmetrical peaks on both sides of center wavelength 1 550 nm in the pass band are the same. It's well known that the energy localization forms slow light transmission. The single defect layer in 1D PC only confines the energy of narrow frequency band of defect peak in PBG. However, multiple cavities can confine energy of broadened band, so it can support wide band slow light transmission.

At first, we analyze the bandwidth variations of slow light in the 1D PC CROW with different cavities spacing M. Fig.4(a) shows the transmission spectra with M=4, 5 and 6, and the corresponding bandwidths of slow light are 37.9 nm, 20.2 nm and 10.7 nm, respectively. Obviously, with the increase of cavities spacing, the bandwidth of slow light pass band is narrowed and flattened. Moreover, When M=6, three peaks in the center of pass band are combined to one broadened peak. Fig.4(b) depicts the transmissions of spectrum trough with M=3, 4, 5 and 6, and the inset depicts the flatness of transmission spectrum versus cavities spacing M. It is shown that when M increases, the transmission peaks are close, and transmission of trough is higher. Results show that the minimum of transmission in the pass band is increased from 0.132, 0.288, 0.380 with M=4 to 0.299, 0.636, 0.829 with *M*=5 and 0.385, 0.810 with *M*=6. Simultaneously, the flatness of $(T_{\max}\text{-}T_{\min})/2$ decreases with the increase of *M*, i.e., the pass band is smoothed effectively, but the bandwidth becomes narrow. Therefore, while choosing suitable cavities spacing, there is a tradeoff between flattening and broadening of slow light.



(a) 1st and 7th peak wavelengths (b) 2nd and 6th peak wavelengths



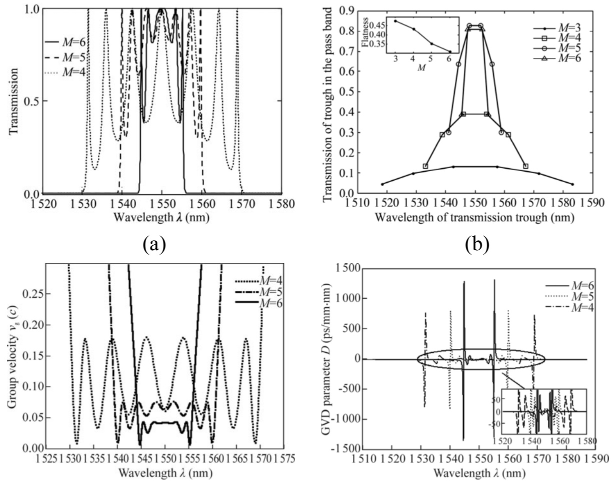
(c) 3rd and 5th peak wavelengths (d) Center peak at 1 550 nm

Fig.3 The electric field distributions in 1D PC CROW structure at different wavelengths in the slow light pass band

Fig.4(c) shows the variation of group velocity v_g with wavelength as *M*=4, 5 and 6, and in the pass band, v_g is in the range of 0.010 6*c*–0.182 1*c*, 0.010 6*c*–0.077 7*c* and 0.008 6*c*–0.044 8*c*, respectively. v_g gradually decreases as *M* increases. The curves clearly show that v_g slightly changes in the slow light pass band, and this change is corresponding to uneven transmission spectrum. When the pass band is flattened and narrowed, the group velocity is decreased and smoothed. According to the coupled mode theory[26], the wider the cavities spacing is, the more tightly the mode is confined, and the mode coupling between adjacent defect cavities becomes weaker, then the propagation velocity of light becomes slower.

In Fig.4(d), GVD parameter *D* is shown as a function of wavelength with *M*=4, 5 and 6. At the band edge, the GVD parameter *D* changes sharply; in the center of the pass band, *D* is smaller and varies slightly. In the smooth center, when *M*=4, GVD parameter *D* is in the range from -62.598 7 ps/(mm·nm) to 63.407 4 ps/(mm·nm), when *M*=5, *D*=-61.638 5–60.301 2, and when *M*=6, *D*=-79.561–78.909 2, which is much smaller than that at the band edge, where *D*=777.065 9, 812.879 5 and 1 325.9. In short, with the increase of the cavities spacing, the broadened slow light band is obviously smoothed, and group velocity v_g is also slow down. At the same time, the bandwidth becomes narrow and GVD parameter *D* deteriorates slightly.

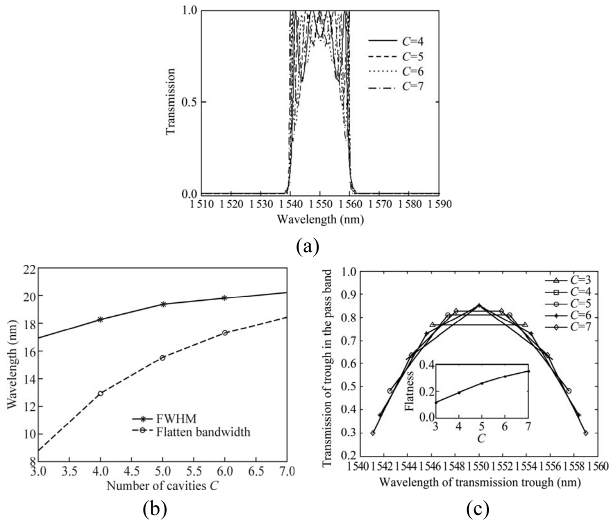
Micro-cavities in CROW confine most of the energy of slow light mode[26]. It determines the properties of the slow light transmission. The slow light properties with the variation of cavities number *C* are discussed when *M*=5 and *N*=2. Fig.5(a) shows the transmission spectra of 1D PC CROW with *C*=4, 5, 6 and 7. When the number of cavities increases, the bandwidth of pass band changes slightly. Fig.5(b) depicts the change of full width of half maximum (FWHM) bandwidth and the bandwidth of smooth GVD within the pass band as a function of cavities number. Compared with Fig.5(a), the flatter the transmission spectrum is, the smaller the GVD parameter *D* is. As shown in Fig.5(a), the pass band is flattened clearly when *C* decreases. The flatness almost linearly decreases as *C* changes from 7 to 3. Fig.5(c) plots the transmissions of trough in the pass band when *C*=3, 4, 5, 6 and 7. The inset of Fig.5(c) depicts the flatness of transmission spectrum versus cavities number *C*.



(a) (b)

(c) (d)

Fig.4 (a) Transmission spectra, (b) transmissions of spectrum trough, (c) group velocities and (d) GVD parameters *D* of pass band of 1D PC CROW with different cavities spacings (The inset of (b) depicts the flatness of transmission spectrum versus *M*.)



(a)

(b) (c)

Fig.5 (a) Transmission spectra, (b) FWHM bandwidths and D-flatten bandwidths and (c) the transmittances of spectrum trough of 1D PC CROW with different cavities numbers *C*=4, 5, 6, and 7 (The inset of (c) depicts the flatness of transmission spectrum versus *C*.)

Fig.6 shows the group velocity variations of pass band with different cavities numbers as a function of wavelength. When *C* increases from 4 to 7, v_g in the pass band varies slightly. Fig.7 shows the variations of GVD parameter *D* as a function of wavelength with different *C*. Clearly, there is a serious oscillation and large dispersion at the band edge. In the middle of the slow light band, the GVD parameter *D* is relatively flat, and when cavities number *C* decreases from 7 to 4, the parameter *D* also decreases. But the width of flat *D* region becomes narrower than the bandwidth of FWHM as shown in Fig.5(b).

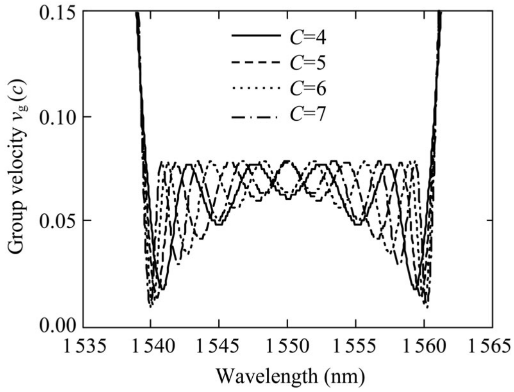


Fig.6 Group velocities of pass band as a function of wavelength as *C*=4, 5, 6 and 7

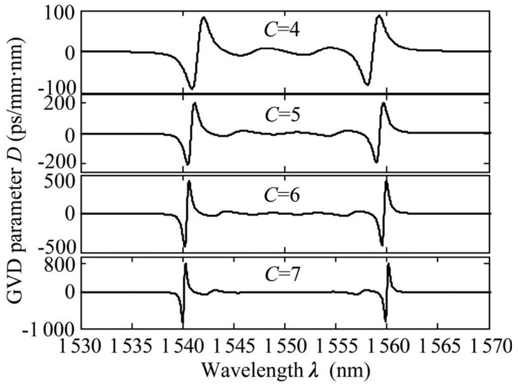


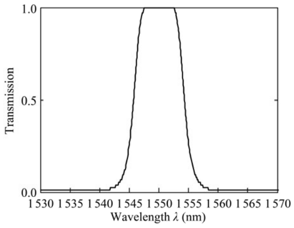
Fig.7 GVD parameters *D* of pass band as a function of wavelength as *C*=4, 5, 6 and 7

Tab.1 summarizes the slow light parameters of 1D PC CROW with different cavities numbers *C*. From Figs.5–7 and Tab.1, the results show that both of flatness and GVD parameter *D* are improved with the decrease of cavities number. But the pass band bandwidth of FWHM and flat *D* become narrow, group velocity v_g worsens at the same time, and the change of v_g is slight. The bandwidth of flat *D* is smaller than that of FWMH, because there is serious GVD at the band edge of FWMH. So there is a tradeoff between flatness, GVD and bandwidth of slow light as adjusting the cavities number.

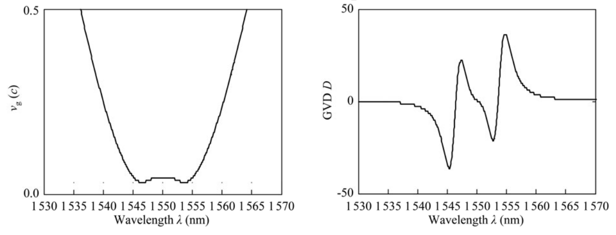
In the practical application, it is desired to obtain wide and smooth slow light pass band with low GVD. Based on the discussion above, here we improve the slow light properties by optimizing the 1D PC structure. We increase the cavities spacing, and decrease the number of cavities to smooth the slow light pass band with considerable width, low group velocity and GVD. We set *M*=6, *C*=3 and *N*=2, and then the 1D PC structure can be depicted as $M_{end}/(C/M_{in})^2CM_{end}$. Fig.8 shows the transmission spectrum, group velocity and GVD parameter *D* after structure optimization. The transmission spectrum shows that an extremely flat pass band with trough transmission more than 0.998 1 is obtained. The flatness is smaller than 9.5×10^{-4}, which is smooth enough to carry broadband conformal slow light transmission. The pass band width of FWHM is 8.556 1 nm with group velocity from 0.029*c* to 0.042 4*c*. The GVD parameter *D* is in the range from -14.410 3 ps/(mm·nm) to 15.124 ps/(mm·nm) around the zero dispersion point within the pass band.

Tab.1 Slow light properties of the 1D PC CROW with different cavities numbers

C	*T*	Flatness	v_g (*c*)	*D* [ps/(nm·km)]	Δλ-FWHM (nm)	Δλ-*D* (nm)
3	0.766 1–1.0	0.117 0	0.030 8–0.073 6	-6.233 9–6.305 0	16.9	8.8
4	0.616 9–1.0	0.191 6	0.023 1–0.075 4	-9.409 7–9.567	18.3	12.9
5	0.481 6–1.0	0.259 2	0.017 5–0.076 4	-16.545–16.079 1	19.3	15.5
6	0.376 9–1.0	0.311 6	0.013 5–0.077 2	-33.926 6–32.684 8	19.8	17.3
7	0.299 3–1.0	0.350 4	0.010 6–0.077 7	-57.021 2–58.393 4	20.2	18.4



(a) Transmission spectrum

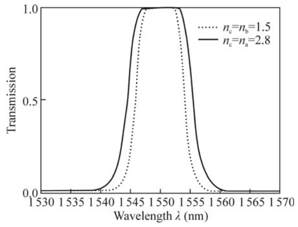


(b) Group velocity (c) GVD parameter *D*

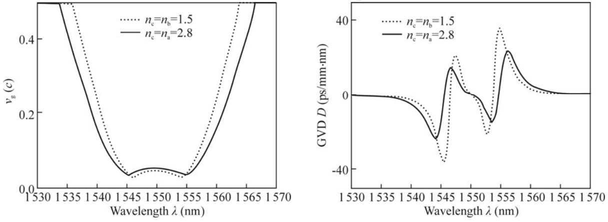
Fig.8 Transmission properties of 1D PC CROW after structure optimization with *M*=6, *N*=2 and *C*=3

In order to further broaden the slow light pass band, the refractive index of PC fundamental material is discussed. Firstly, we set the defect cavity material to be the higher refractive index, i.e., $n_c=n_a=2.8$. Fig.9 shows the transmission properties compared with those of the optimized 1D PC CROW mentioned above with $n_c=n_b=1.5$. Increasing the refractive index of cavity layer, the slow light pass band is broadened from 8.556 1 nm to 10.896 5 nm, the flatness decreases to 8.8052×10^{-4}, and is smaller than that of the former one, the GVD parameter D decreases to the range of -9.2908–9.6752 ps/(mm·nm). But the performance of group velocity becomes worse slightly: it increases from $0.0294c$–$0.0424c$ to $0.0348c$–$0.0509c$.

Secondly, we set n_b=1.5 and n_a=n_c, adjusting n_a and n_c from 2.8 to 2.3 at interval of 0.1, and the transmission properties are shown in Fig.10. The pass band is gradually broadened as n_a and n_c increasing step by step. The GVD parameter D is also improved, and it decreases to the range of -2.520 1–2.598 9 ps/(mm·nm) gradually. However, the flatness decreases slightly, and the minimum transmission on trough decreases from 0.998 2 to 0.9765. At the same time, the group velocity v_g worsens with the decrease of n_a.

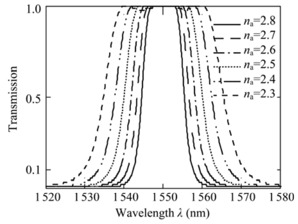


(a) Transmission spectra

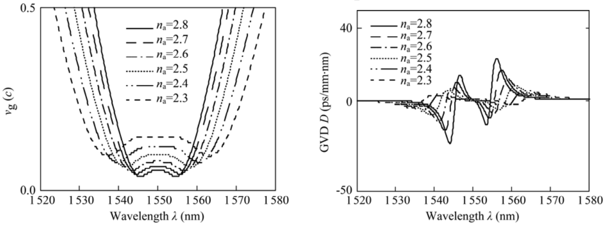


(b) Group velocities (c) GVD parameter D

Fig.9 Transmission properties of the optimized 1D PC CROW with n_c=1.5 and optimized material with n_c=2.8



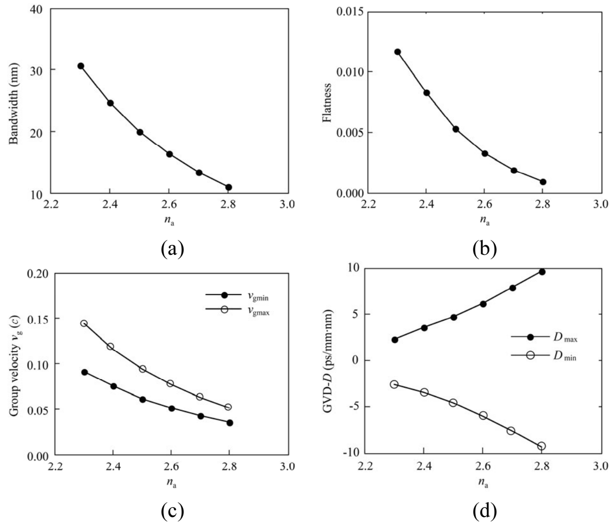
(a) Transmission spectra



(b) Group velocities (c) GVD parameter D

Fig.10 Transmission properties when n_a and n_c change from 2.8 to 2.3

The properties of bandwidth, flatness, group velocity and GVD parameter D curves versus n_a are shown in Fig.11. As n_a decreasing, the bandwidth, flatness and group velocity all increase exponentially. In addition, the GVD parameter D almost linearly decreases. Considering the practical application of slow light, the group velocity can not be too large. So, in our optimized structure, n_a should not be larger than 2.5. As n_a=2.5, v_g is from $0.054c$ to $0.083c$, and bandwidth is 20.0578 nm in the wavelength range of 1 540.0–1 560.1 nm. The bandwidth increases by about 2.3 times than that of structure with n_a=2.8 (8.8052 nm), and by 25.07 times than that of single defect transmission peak. The flatness is 5.4×10^{-3}, and GVD parameter D is from -4.6578 ps/(mm·nm) to 4.7904 ps/(mm·nm). It can support slow light pulse with sufficient bandwidth and acceptable distortion.



(a) (b)

(c) (d)

Fig.11 (a) Bandwidth, (b) flatness, (c) group velocity and (d) GVD parameter D as a function of n_a

In summary, by introducing multiple defect cavities, flat broadband slow light transmission with low dispersion in 1D PC CROW structure is investigated. By tuning the spacing and number of cavities, the pass band of slow light is smoothed. At the same time, the GVD is also obviously improved. Using optimized structure of M=6, C=3 and N=2, the bandwidth of slow light pass band can be broadened to 8.5561 nm, the flatness is less than 8.8052×10^{-4}, GVD parameter D decreases to the range of -14.4103–15.124 ps/(mm·nm), and group velocity is v_g=$0.0294c$–$0.0424c$. Moreover, by material optimization, the slow light properties are improved further. With n_a=n_c=2.5 and n_b=1.5, the flat slow light bandwidth can reach as wide as 20.0578 nm, and the GVD parameter D decreases to -4.6578–4.7904 ps/(mm·nm). It can support slow light pulse with sufficient bandwidth and acceptable distortion.

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