Research on slow light transmission with wide bandwidth and large normalized delay bandwidth product*

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(Received 1 August 2020; Revised 23 September 2020)

In order to obtain excellent slow-light performance, we propose a photonic crystal waveguide (PCW) that introduces extrinsic defect rods in the center row of a complete square lattice rotated 45° counterclockwise and the second row adjacent to it. The continuous cavities are used as a storage of electromagnetic energy and a speed reducer of light speed, used for slow optical transmission in PCWs. Then, the plane wave expansion method (PWE) is used to study the slow light transmission characteristics of the proposed structure, and the influence of the structure parameters on the slow light performance is analyzed. Finally, the bandwidth is obtained at 23.37 nm when the normalized delay bandwidth product (*NDBP*) reaches 0.40. In addition, considering the effect of material properties on slow light performance, *NDBP* is further optimized to 0.44, and the bandwidth reaches 27.63 nm. A simple but universal structure is designed to provide an important theoretical basis for further improving the storage capacity with high bandwidth and high *NDBP* slow light.

Document code: A **Article ID:** 1673-1905(2021)07-0407-5
DOI https://doi.org/10.1007/s11801-021-0125-3

For all integrated optical components, it is very important to minify the device size and cut down energy consumption, which can reduce production and operating costs. Slow light in photonic crystal waveguides (PCWs) has special potential in this regard[1]. In addition, PCWs can be produced at room temperature, and provide wide bandwidth[2], low dispersion[3] and less distortion. The slow light effect can be applied to optical devices such as optical buffers and optical retarders[4].

A key parameter in a comprehensive evaluation of slow light performance is the normalization delay bandwidth product (*NDBP*), which maximizes buffer capacity and delay time. Here must take some steps to balance low dispersion broadband with large group index, and researchers have designed different PCWs to achieve higher *NDBP*. Most of the designed structures are constructed along two main ideas, changing the array of scattering elements or changing the structure of the scattering elements. In 2013, Wan Yong[5] used gradient arcuate scattering elements to achieve slow light and obtain ultra-low light. The bandwidth of the dispersion is only 4.2 nm at the same time. In 2016, Na Zhu[6] have improved the slow light performance by introducing a slot waveguide structure. But the final *NDBP* value is only 0.24, the slow light effect is not good. In 2017, Dang S[7] used a square lattice rotated 45° counterclockwise to analyze the influence of the radius of the middle three rows of dielectric cylinders on the slow light performance, and the result was a narrow bandwidth. In 2018, Yi Jia[8] use an air ring scattering element structure to reduce the group velocity and the bandwidth is also greatly reduced. In 2019, Abood I[9] proposed PC-CCW to improve slow light performance, structure does not have good scalability.

In this paper, in order to obtain better slow light properties, other defects need to be introduced into the waveguide. First, a new lattice structure is obtained by rotating the square lattice counterclockwise by 45°, and then a series of extrinsic defect rods are introduced to form a series of cavities to improve the slow light properties of the waveguide. Based on the plane wave expansion method, the single variable method is used to analyze the structural parameters that affect the slow light characteristics one by one, analyze the results, and adjust the values of the structural parameters to achieve better slow light.

The slow light phenomenon in photonic devices has important applications in optical signal processing, device size reduction, and noise reduction. Therefore, the dispersion and slow light based on PCWs play a vital role in the field of optical communication and optical signal processing. The dispersion relationship of the mode is related to the extrinsic material, the characteristics of the intrinsic material, and the geometric structure of PhC. In order to optimize the parameters that characterize the slow light performance, the two-dimensional

* This work has been supported by the Gansu Natural Science Foundation (No.1610RJZ046).
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square lattice is rotated counterclockwise to obtain the perfect photonic crystal structure as shown in Fig.1. The dielectric rod is Si (red color) with a refractive index of 3.46, and the background material is air with a refractive index of 1. Defective dielectric rods are introduced into the perfect photonic crystal. The material of the defect rod is InP (black color) with a refractive index of 3.1. The arrangement of the external defect rods InP is shown in Fig.1. Three linear defects are formed. The materials of the five rows of dielectric columns in the center are Si and InP alternately arranged. The dotted rectangle in Fig.1 is a super cell (super cell size is $\sqrt{2}a\times 6\sqrt{2}a$).

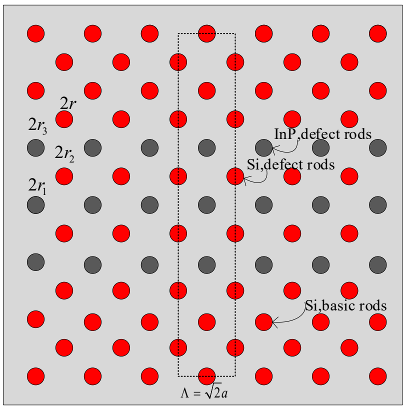


Fig.1 Schematic structure diagram of PCW

Based on Rsoft software, plane wave expansion (PWE) is used to calculate the band gap structure, and three linear defects are considered to optimize slow light performance. Based on this idea, usually, the optimization process is divided into three steps: First, by introducing defect rods in the perfect photonic crystal, the effect on n_g and group velocity dispersion (*GVD*) is obtained. The introduction of the defective dielectric rod needs to be able to generate positive *GVD* and negative *GVD* at different frequencies, so that *GVD* can be approximately zero at certain frequencies; secondly, change the radius of the defective dielectric rods in the center row; then, fix the radius of the rods in the center row to the best value, and change the radius of the rods in the second row near the center row to optimize the slow light performance; in order to optimize the influence of the first row of dielectric rods on *GVD* and bandwidth, finally, fix the radius of the second row of dielectric rods to the value when the normalized delay bandwidth product is maximum, and change the radius of the first row of dielectric rods.

One of the important factors to measure slow light is the group velocity, which is defined as the reciprocal of the group refractive index[5]:

$$v_g=\frac{d\omega}{d\kappa}=\frac{c}{n_g}, \tag{1}$$

where n_g is the group refractive index, v_g is the group velocity, ω is the angular frequency, κ is the wave vector, and c is the speed of light. *GVD* is a characteristic of a dispersive medium, defined by the derivative of the reciprocal of the group velocity with respect to the angular frequency:

$$GVD=\frac{a}{2\pi c^2}\frac{dn_g}{dU}=\frac{a}{2\pi c}\frac{d}{dU}\left(\frac{1}{v_g}\right), \tag{2}$$

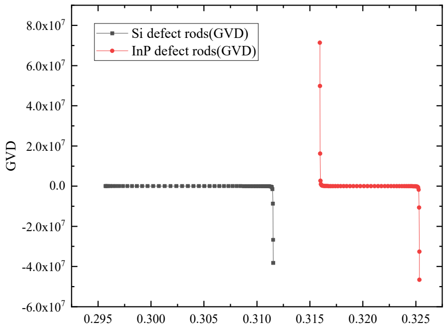
where U is the normalized frequency, $U=\omega a/2\pi c=a/\lambda$, and the parameters n_g and *GVD* as a function of U can be obtained from the dispersion curve of PCWs. The pros and cons of slow light in PCWs are described by using parameters n_g, v_g, normalized bandwidth, *GVD* and *NDBP*. These parameters directly affect system performance. However, the group refractive index of a given structure is inversely proportional to the bandwidth. *NDBP* can measure the performance of slow light from multiple angles, it is defined as the product of the average group refractive index and the normalized bandwidth[10]:

$$NDBP=\langle n_g\rangle\cdot\frac{\Delta\omega}{\omega_0}, \tag{3}$$

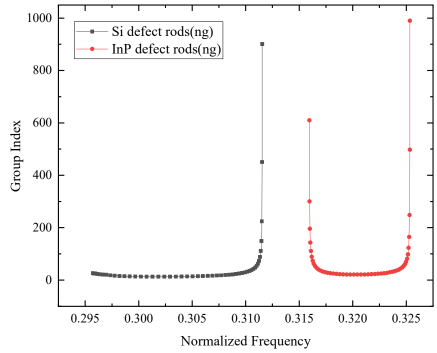
where $\langle n_g\rangle$ is the average group refractive index, within the range of $\pm10\%$ variation, $\Delta\omega$ is the bandwidth, and ω_0 is the center frequency of the bandwidth. The choice of this range is desirable because the problem with most applications is transmission loss rather than dispersion.

The influence of the introduction of the external defect dielectric rods on the slow light performance of PCW was studied in detail. When, analyze the influence on and *GVD* parameters with and without InP defect dielectric column, as shown in Fig.2(a) and (b). From the result graph, it can be concluded that the introduction of InP defect dielectric column produces positive *GVD* and negative *GVD*, which is very important for the application of dispersion compensation. From the comparison chart of group refractive index, it can be concluded that the introduction of InP defect dielectric column has improved the group refractive index to a certain extent, and the minimum value has increased from 12.86 to 20.95. Therefore, it can be concluded that introducing external defects can better improve the slow light characteristics.

First, by changing the radius r_1 in the center row, while keeping the radii of the first and second rows at $r_2=r_3=r=0.20a$, change in steps of $0.01a$ within the range of $0.11a\leq r_1\leq 0.16a$. This range is studied because the *GVD* value needs to be in the range of -10^8—10^8, which is very important for the application of dispersion compensation. The dispersion curve is shown in Fig.3(a). With the increase of r_1, the guided mode curve is shifting from high frequency to low frequency region. Using Eqs.(1) and (2) to solve the first and second derivative parameters of the dispersion relationship, n_g and *GVD* can be obtained, As shown in Fig.3(b) and (c). Tab.1 illustrates the value of *NDBP* describing the pros and cons of slow light. From Fig.3(b) and (c), it can be clearly seen that while maintaining r_2 and r_3, with the decrease of r_1, the group refractive index value continues to increase, and the bandwidth value continues to decrease. Therefore, there is a trade-off between in the group refractive index and bandwidth. Tab.1 shows that when r_1=0.14a, the *NDBP* value reaches a maximum of 0.231 4, at this time the bandwidth $\Delta\lambda$=30.59 nm, group refractive index n_g=11.73.

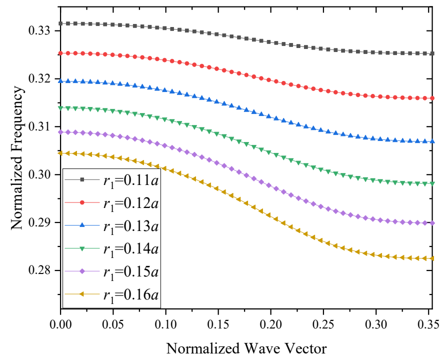


(a) Group index versus normalized frequency

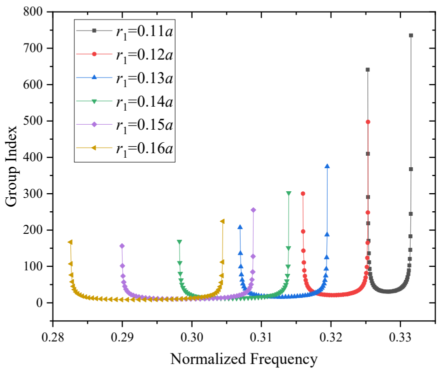


(b) GVD versus normalized frequency

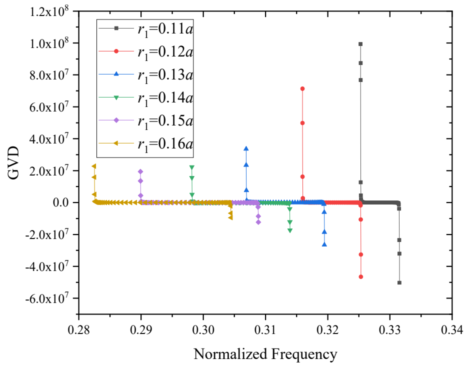
Fig.2 Comparison of slow light properties of PCW without extrinsic defect rods and with extrinsic defect rods



(a) Dispersion curves of guided modes



(b) Group index with normalized frequency



(c) GVD with normalized frewquency

Fig.3 Slow light properties affected by the radius r_1 in the range of 0.11a≤r_1≤0.16a

Tab.1 Slow-light properties affected by the radius r_1 for 0.11a≤r_1≤0.16a and r_2=r_3=r=0.20a

r_1/a	$\Delta\omega$ (×10^4)	$\Delta\omega/\omega_0$ (×10^4)	$\Delta\lambda$ (nm)	n_g	*NDBP*
0.11	22.4	68.2	10.57	28.46	0.194 1
0.12	35.9	112.0	17.35	19.73	0.220 9
0.13	47.7	152.3	23.61	14.85	0.226 2
0.14	60.4	197.3	30.59	11.73	0.231 4
0.15	67.5	225.4	34.95	9.44	0.212 9
0.16	80.5	274.2	42.51	7.92	0.217 3

The propagation speed of the light wave in the waveguide will decrease with the increase of the defective dielectric rod, because more cavities need to be filled with energy, which requires more time, which slows down the propagation speed. On the basis of the previous analysis, in order to realize and maximize the influence of the second row of dielectric rods close to the center row on the bandwidth, n_g and *NDBP*, the fixed size of r_1 is 0.14a and the fixed size of r_2 is 0.20a and the value of r_3 is changed in the range of 0.28a≤r_3≤0.34a, and then analyze its dispersion curve.

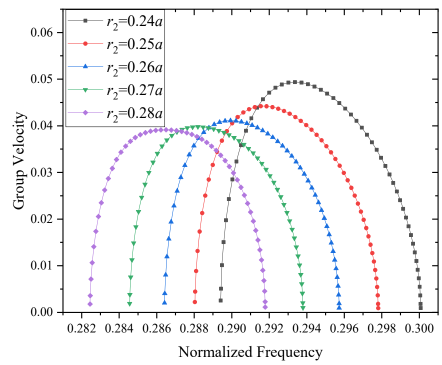
The second row of dielectric rods adjacent to the center row is InP, so it is necessary to analyze the influence of the change of its radius on n_g, bandwidth, *GVD* and *NDBP*. Through the analysis of the radius r_3, it is concluded that the radius value will cause the changes of various parameters, thereby affecting the propagation behavior of light. The bandwidth, group refractive index, and *NDBP* value corresponding to each radius value are summarized in Tab.2. Once again, the bandwidth value is inversely proportional to the group refractive index. Therefore, *NDBP* is an indispensable parameter to measure the slow light performance. When r_3=0.28a, the maximum group refractive index is n_g=12.49 and the minimum bandwidth value is $\Delta\lambda$=37.73 nm. When r_3=0.34a, the minimum group refractive index is n_g=10.74 and the maximum bandwidth value is $\Delta\lambda$=44.16 nm. The value of *NDBP* increases first and then decreases with the increase of the radius value. When r_3=0.31a, the *NDBP* value reaches the maximum value of 0.328 4. The result obtained at this time is the best result that can be obtained by changing the value of r_3, and the result obtained in this step will be used in the next analysis.

Tab.2 Slow-light properties affected by the radius r_3 for 0.28a≤r_3≤0.34a and r_1=0.14a, r_2=r=0.20a

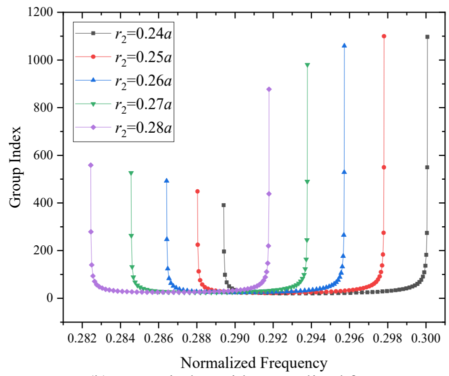
r_3/a	$\Delta\omega$ ($\times10^4$)	$\Delta\omega/\omega_0$ ($\times10^4$)	$\Delta\lambda$ (nm)	n_g	*NDBP*
0.28	73.7	243.4	37.73	12.49	0.304 1
0.29	74.7	246.9	38.28	12.33	0.304 4
0.30	80.9	267.7	41.49	12.25	0.328 1
0.31	82.0	271.6	41.09	12.09	0.328 4
0.32	83.0	275.2	42.65	11.94	0.305 2
0.33	84.3	279.8	43.38	10.92	0.305 6
0.34	85.7	284.9	44.16	10.74	0.306 1

Next, change the radius value of the first line of the dielectric rods adjacent to the center line to maximize the slow light properties through this change.

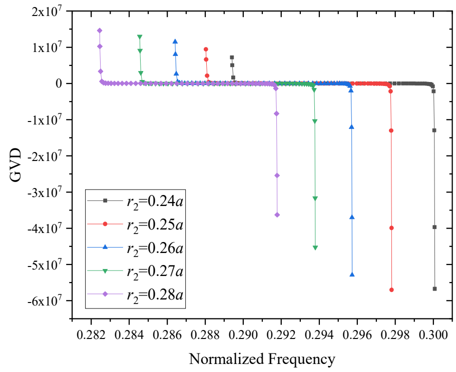
As shown in Fig.4, it is the result of keeping r_1=0.14a and r_3=0.31a unchanged, and changing the value of r_2 from 0.24a to 0.28a in steps of 0.01a. As shown in Fig.4(a) and (b), it shows that as the radius r_2 increases, v_g gradually decreases and n_g gradually increases, and its bandwidth value $\Delta\lambda$ also gradually decreases. As shown in Fig.4(c), changing r_2 makes the *GVD* of the structure stay within -6×10^7—2×10^7, meet the requirements of optical transmission for dispersion value. When r_2=0.28a, the maximum group refractive index n_g is 26.16, and the minimum bandwidth value $\Delta\lambda$ is 23.37 nm. The maximum *NDBP* value at this time is 0.394 4. In order to observe the law more conveniently, summarize the parameter values in Tab.3.



(a) Group velocity with normalized frequency



(b) Group index with normalized frequency



(c) GVD with normalized frequency

Fig.4 Slow light properties affected by the radius r_2 changing from 0.24a to 0.28a with r_1 fixed at 0.14a and r_3 fixed at 0.31a

Tab.3 Slow-light properties affected by the radius r_2 for 0.24a≤r_2≤0.28a and r_1=0.14a, r_3=0.31a

r_2/a	$\Delta\omega$ ($\times10^4$)	$\Delta\omega/\omega_0$ ($\times10^4$)	$\Delta\lambda$ (nm)	n_g	*NDBP*
0.24	50.0	169.6	26.29	18.41	0.312 3
0.25	45.1	154.0	23.86	21.98	0.338 4
0.26	44.7	153.6	23.80	22.17	0.340 5
0.27	43.6	150.8	23.38	24.35	0.367 1
0.28	43.3	150.8	23.37	26.16	0.394 4

For the proposed PCWs structure, a complete analysis of its structural parameters has been carried out. The obtained structural parameters are when fixed r=0.20a, and at the same time r_1=0.14a, r_2=0.28a, r_3=0.31a, the slow light effect is optimal at this time. Compare this result with the results obtained without introducing three rows of InP defective dielectric rods under the same structural parameters, and the results are shown in Tab.4. It can be seen from the comparison that the introduction of InP intrinsic defects increases the bandwidth by 1.5 times, which increases the group index by 1.4 times, and at the same time increases the value of NDBP by 2.2 times.

Tab.4 Comparison of slow light characteristics when introducing InP extrinsic defects and Si intrinsic defects

Type of defect	$\Delta\omega$ ($\times10^4$)	$\Delta\omega/\omega_0$ ($\times10^4$)	$\Delta\lambda$ (nm)	n_g	NDBP
With InP defect	43.3	150.8	23.37	26.16	0.394 4
With Si defect	27.3	100.5	15.57	18.14	0.182 3

The material properties and the design of the waveguide structure will affect the slow-light characteristics. The above content discusses the influence of the structural parameters on the slow-light properties, and then discusses the changes of the material characteristics on the slow-light performance. On the basis of the above analysis of the silicon-based dielectric rods, keep the radius value unchanged, the background material and the material of the introduced defect dielectric rods remain unchanged, use different refractive index media to fill the basic dielectric rods, and the refractive index change takes six cases. The results are shown in Tab.5. It can be concluded from Tab.5 that the change of the refractive index greatly changes the slow light performance. With the increase of the refractive index value, the guided mode curve and the center frequency move to the low frequency region, while the bandwidth value gradually decreases, and the group refractive index value gradually increases. An important factor for measuring slow light performance, the *NDBP* value first increases and then decreases. When refractive index is 3.43, the *NDBP* value reaches 0.442 7. Compared with the basic dielectric rods as Si, the *NDBP* value has been significantly improved. Therefore, when improving slow light performance, material properties are also an important factor.

Tab.5 Comparison of slow light performance under different refractive index conditions

Refractive index	ω_0	$\Delta\lambda$ (nm)	n_g	*NDBP*
3.25	0.292 5	38.00	15.80	0.387 3
3.30	0.291 3	36.50	16.51	0.388 9
3.35	0.290 1	32.29	19.31	0.414 7
3.40	0.289 0	30.31	21.30	0.416 4
3.43	0.287 8	27.63	24.83	0.442 7
3.46	0.287 1	23.37	26.16	0.394 4
3.55	0.285 5	20.52	28.08	0.371 8

Tab.6 compares the achievable results of the structural improvement in this paper with the previous literature. It can be seen from the comparison chart that the final results obtained in this paper have been greatly improved in bandwidth and *NDBP*.

Tab.6 n_g, $\Delta\lambda$ at 1 550 nm and *NDBP* in current work as compared with those in previous works

References	$< n_g >$	$\Delta\lambda$ (1 550 nm)	*NDBP*
Current work	24.43	27.63	0.442 7
[11]	23.0		0.385
[12]	24.01		0.272 8
[13]	850	0.668 9	0.378
[14]	21	20.3	
[15]	20.1	23.04	0.308 3
[16]	373.4	0.068	
[7]	48	12.21	0.378
[6]			0.245

In this paper, three linear defect photonic crystal waveguides composed of extrinsic defect InP dielectric pillars are introduced into a square lattice rotated 45° counterclockwise to realize slow optical transmission with high bandwidth and high *NDBP*. By changing the radius of the defective dielectric column, the optimization of parameters for measuring slow light performance is completed. Structural parameters after optimization: r_1=0.14a, r_2=0.28a, r_3=0.31a, $\Delta\lambda$=23.37 nm, n_g=26.16, and *NDBP* is 0.394 4, meanwhile the value of *GVD* is within the range of ensuring no distortion during optical transmission. On the basis of studying the structural parameters, the material properties are analyzed, and finally the bandwidth of 27.63 nm is obtained while the *NDBP* reaches 0.442 7. The influence of the central row dielectric column and its adjacent two rows of defective bars on the bandwidth and *NDBP* is studied. Comparing this result with the structure without extrinsic defects under the same structural parameters, each performance parameter has been improved. Compared with Ref.[7], both adopt a square lattice structure rotated 45° counterclockwise, but the bandwidth of this paper is increased by nearly twice, and the comprehensive parameter *NDBP*, which measures slow light performance, is also significantly improved. Therefore, this structure provides a new idea and method for the future development of photonic crystal buffers.

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