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Design of wideband and low group velocity based on coupled cavity waveguides

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ABSTRACT

A method is proposed to design wideband and low group velocity in coupled cavity waveguide (CCW). By tuning the position of the defect row, the first and second rows adjacent to the defect row in the photonic crystal, the guided band is tailored. As a result, the group velocity can be decreased, with a relatively broad bandwidth of the guided band. The effects of three parameters on the group velocity of the crystal are analyzed in detail, using 2D plane wave expansion method. We numerically demonstrate that the group velocity of 0.0096*c* with 3.0 nm bandwidth of the guided band can be obtained in the model. Viewed from an actual standpoint, this tuning position method has its advantage in fabricating than the method of controlling the diameters of rods or holes.

1. Introduction

Photonic crystals (PhCs) are structures with periodic reflective index, which were first proposed by Yablonovitch and John in 1987 [1,2]. Due to the photonic band-gap (PBG), which is produced by the periodic structure, the PhC has great advantages in controlling light [3,4]. The photonic crystal waveguide (PhCW), which has a line defect in the PhC, can guide light in the defect region [5]. It could not only prohibit light with a specific frequency propagating in the PhC, but also control the speed of the light according to the structure dispersion [6]. In the PhCW, slow light is a valuable solution for optical delay line devices [7,8], buffering [9,10], memory [11], time-domain optical signal processing devices [12], etc. A lot of research about slow light has been reported in recent years. Among them, there are slotted PhCW [13,14], PhC slab [15], PhC rods [16], coupled cavity waveguide [17], ring-shape-hole photonic crystal waveguide [18], etc. And most researches are committed to achieving a low group velocity v_g and a broad bandwidth $\Delta\lambda$ [19,20], since the actual optical input (e.g. short pulses or high-speed modulated signals) usually has a wide spectrum. However, the bandwidth of the guided band in most PhCW with the very low v_g (e.g., $<0.01c$) is very narrow (e.g., <0.1% of the central wavelength) [21].

The various structures in PhCWs have shown their different optical properties and advantages. The CCW with dielectric rods in air shows a broader PBG in band diagram than the PhC slab with air holes [4] and they are easy to fabricate in reality [22]. To get a structure with a low group velocity v_g and a broad bandwidth $\Delta\lambda$, a coupled cavity waveguide with triangular lattice of rods in air is studied. The parameters of this CCW and their effects on the group velocity v_g are systematically discussed. Finally, the optimal parameters of this CCW to get a low group velocity and a broad bandwidth are given.

2. Design and modeling

Considering a photonic crystal, which has infinite triangular lattice of rods with the dielectric constant $\varepsilon = 11.56$ (corresponding to Si in the infrared region [23]) in air background. The radius of the rods is $r = 0.18a$ (where a is the lattice constant). Every other rod in the central row is removed in our model. The distance of every two adjacent cavities in the center of the CCW $R = 2a$ is shown in Fig. 1. The supercell method is used in the calculation [4]. The supercell size is chosen to be $R \times 11a$, which is large enough that the coupling between the adjacent parallel waveguides can be neglected.

In order to analyze the characteristic property of the CCW, the dispersion curves for TM-polarized light-waves are calculated, in which the direction of the electric field is in parallel with the dielectric cylinders. The MIT photonic-band package (MPB) is adopted, which is a software adopting the plane wave expansion method (PWEM), to stimulate the band diagram of the 2D PhCW. For the CCW, the guided mode is in the center of the PBG as shown in Fig. 2. The group velocity v_g of the guided mode can be got from the slope of the dispersion curve.

$$v_g = \frac{d\omega}{dk} = \frac{c}{n_g}$$

In this formula, ω is the frequency, k is the wavevector in the propagation direction (it is k_x in our model), c is the velocity of light in vacuum, and n_g is the group index. From the diagram, we can see

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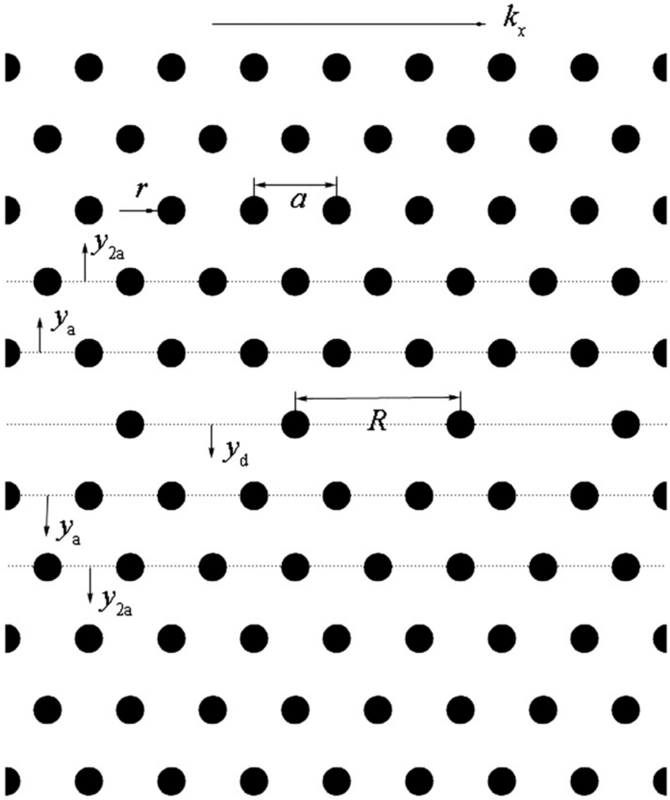

Fig. 1. An infinite triangular lattice of dielectric cylinders. Dielectric constant $\varepsilon = 11.56$, radius $r = 0.18a$. k_x represents the wave vector. Cavity distance $R = 2a$. $y_d = 0a$, $y_a = 0a$, $y_{2a} = 0a$. Dashed lines represent the position of the row. The arrows of y_d, y_a, y_{2a} represent the positive direction respectively.

that the group velocity is decreased in the larger wavevector region. Near zero slope can be got near the band edge, which means that the group velocity of the guided mode is decreased to zero at the band edge. The upper and lower cutoff frequencies are also illustrated in Fig. 2, which can be used to calculate the bandwidth. If the rods are finite in our model to conform with the practical problems, there would be an extra light line in the band diagram [4]. This would not affect the guided band in the band diagram and the group velocity of the CCW. As a result, only 2D situation is considered in the study.

The effects of the cavity distance R on the group velocity v_g are studied. The group velocity v_g and the bandwidth of the guided band $\Delta\lambda$ are calculated when $R = 2a$, $3a$, $4a$, $5a$, respectively. Here the bandwidth equals the difference between the upper cutoff frequency f_u and the lower cutoff frequency f_l of the guided band (subscript u represents upper and subscript l represents lower). With increased R, the distances between the central hexagonal cavities are increased. Thus the coupling between the hexagonal cavities is weakened. This induces the guided band to become gentler and the group velocity is decreased. Moreover the increasing R makes that the dimension of the supercell in the propagation direction is increased. Thus the reciprocal wavevector in this direction is decreased and the bandwidth of guided band is also decreased. We calculate the group velocity v_g, the bandwidth $\Delta\lambda$, the ratio of v_g and $\Delta\lambda$, respectively, as shown in Table 1. To get a low group velocity v_g and a large bandwidth $\Delta\lambda$, R is selected $2a$ in the calculation model.

In general, the group velocity v_g and the group index n_g depend on the CCW configuration and structural parameters. We use three configuration parameters y_d, y_a and y_{2a} to tune the group velocity v_g and the group index n_g. Here y_d represents the distance away from the center line of the defect rods (subscript d represents defect); y_a represents the distance of the rods in the adjacent row to the defect line away from the original position (subscript a represents adjacent); y_{2a} represents the distance of the rods in the second lines off the defect line away from the original position (subscript 2a represents the second line adjacent to the defect line) as shown in Fig. 1. In the study, it is found that these three parameters have the advantage of reducing the group velocity v_g and tuning the positions of rods is easy to realize in practical fabrications.

Firstly, when y_a and y_{2a} are kept unchanged, v_g is decreased and then increased as y_d is increased from $0a$ to $0.35a$. Specifically, with $y_a = 0a$ and $y_{2a} = 0a$, v_g is decreased from $0.12c$ to $0.01c$ when y_d is increased from $0.08a$ to $0.30a$, and v_g is increased from $0.01c$ to $0.04c$ when y_d is increased from $0.30a$ to $0.35a$ as shown in Fig. 3. Thus there is an inflection point at $y_d = 0.30a$. To explain this phenomenon, it is necessary to divide the hexagonal cavity into two small cavities: the upper cavity and the lower one. The transmission property of light in the CCW is related to the coupling of the cavities in the

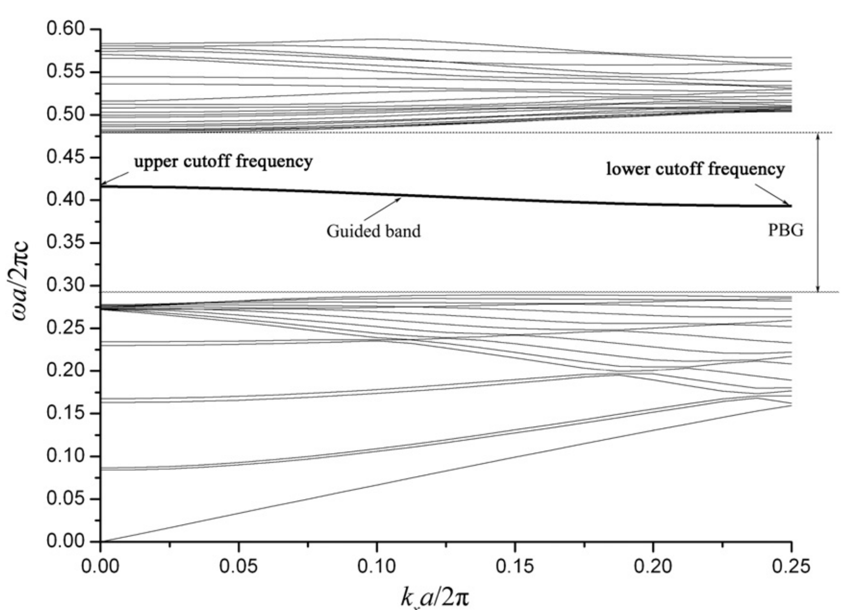

Fig. 2. Calculated dispersion curve of a CCW, where $r = 18a$, $\varepsilon = 11.56$. Thick line represents the dispersion relation of the guided band of the CCW. Here, y_d, y_a, y_{2a} are set to 0.

Table 1
The variation of the group velocity v_g, the upper cutoff frequency f_u, the lower cutoff frequency f_l, the bandwidth $\Delta\lambda$ and the ratio of v_g and $\Delta\lambda$ with the cavity spacing *R*.

R	v_g/c	$f_u(\omega a/2\pi c)$	$f_l(\omega a/2\pi c)$	$\Delta\lambda/(\omega a/2\pi c)$	$v_g/\Delta\lambda(c\lambda/a)$
2*a*	0.1422	0.419168	0.396352	0.022816	6.23246844
3*a*	0.04242	0.409462	0.404935	0.004527	9.370444
4*a*	0.0108	0.40758	0.406716	0.000864	12.5
5*a*	0.00208	0.407228	0.407062	0.000166	12.5301205

CCW. From the coupling mode theory [24], it is known that the coupling strength of the cavities affects the bandwidth of the guided band. Thus the relation between v_g and the parameter y_d can be illustrated theoretically. With increased y_d, the lower cavity of the original hexagonal cavity is compressed and the coupling between the lower cavities is becoming weaker. This alteration produces a broader bandwidth of the guided band and makes the guided band in the PBG gentler. Accordingly, the slope of the guided band is decreased and v_g is decreased too. On the other hand, the increasing of y_d enlarges the upper cavity of the original hexagonal cavity and makes the coupling between the upper cavities stronger. This alteration produces a narrower bandwidth of the guided band and makes the guided band steeper. Thus the slope of the guided band is increased and v_g is increased too. Based on the above two reasons, v_g is first decreased and then increased with the increasing y_d. Since the points collected are not concentrated enough, the inflection point is sharp in Fig. 3.

Secondly, when y_d and y_{2a} are kept unchanged, v_g is decreased and then increased as y_a is increased from $y_a = -0.26a$ to $y_a = 0.30a$. Specifically, with $y_d = 0a$ and $y_{2a} = 0a$, v_g is decreased from 0.114*c* to 0.013*c* when y_a is increased from $y_a = -0.26a$ to $y_a = -0.17a$ and v_g is increased from 0.013*c* to 0.235*c* when y_a is increased from $y_a = -0.17a$ to $y_a = 0.30a$ as shown in Fig. 4. To explain this phenomenon, not only the hexagonal cavities in the center, but also the interstice between the rods in the lines adjacent to the center line and the rods in the second lines off the center line are needed to be considered in our study. To some extent, this interstice can be regarded as subsidiary cavities, which are on both sides of the hexagonal cavities in the center. With increased y_a, the subsidiary cavities are compressed, which means that the coupling between the subsidiary cavities and the central hexagonal cavities is weakened. Thus the bandwidth of the guided band is narrowed and the group velocity v_g is decreased. At the same time, the central hexagonal cavities are enlarged with the increased y_a, and the coupling between

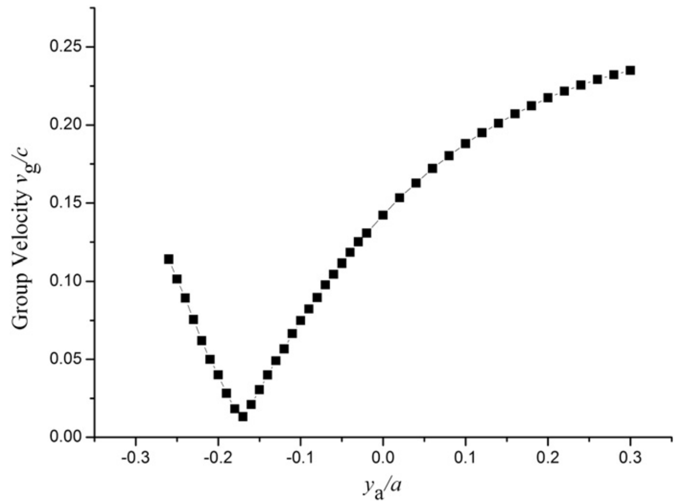

Fig. 4. The group velocity v_g as the function of y_a.

the hexagonal cavities is strengthened. As a result, the bandwidth of the guided band is broadened and the group velocity v_g is increased. Accordingly, the group velocity v_g is decreased and then increased with the increasing y_a.

Thirdly, when y_d and y_a are kept unchanged, v_g is decreased as y_{2a} is increased. Specifically, with $y_a = 0a$ and $y_d = 0a$, v_g is decreased from 0.17*c* to 0.10*c* when y_{2a} is increased from $-0.35a$ to 0.35*a* as shown in Fig. 5. Similarly, considering the subsidiary cavities we can also explain this phenomenon using the coupling mode theory. With increased y_{2a}, the subsidiary cavities are compressed, which means that the coupling between the subsidiary cavities and the central hexagonal cavities are weakened. As a result, the bandwidth of the guided band is narrowed and the group velocity is also decreased.

In the calculation, it is found that the central wavelength is increased when y_d, y_a and y_{2a} are increased separately. But the variation is not large enough to affect the ratio of the bandwidth to the central wavelength. As a result, the variation of the central wavelength is neglected in this paper.

Based on the discussion above, these three parameters are tuned simultaneously to obtain a low group velocity and a relatively broad bandwidth of the guided band and it is found that the best points are not at the inflection points of Figs. 3 and 4. Though to get a low group velocity, y_d, y_{2a} are increased and y_a is decreased, the values

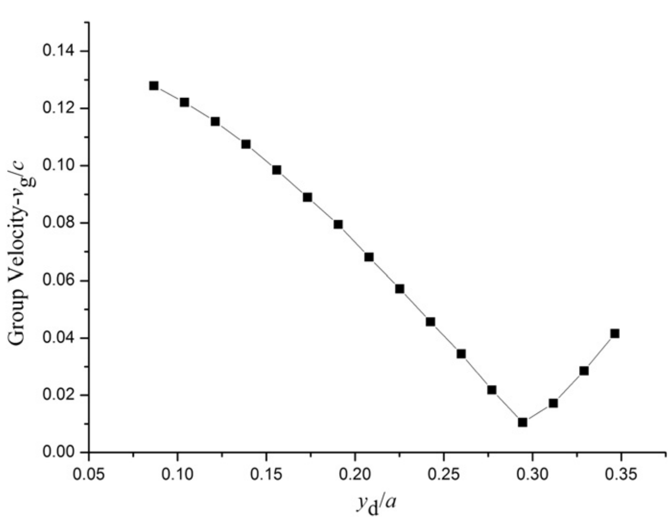

Fig. 3. The group velocity v_g as the function of y_d.

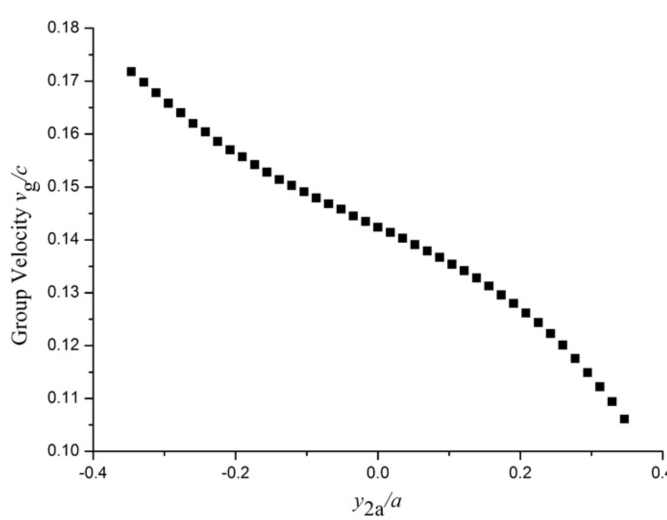

Fig. 5. The group velocity v_g as the function of y_{2a}.

changed are not equal to the values changed in Figs. 3–5, because the three parameters influence each other.

The simulation steps to get the optimized parameters are expatiated as follows. Firstly, a certain y_d and certain y_a are chosen. Then the calculation of the group velocity for different y_{2a} is done. From these data, a y_{2a} is chosen with the minimum v_g and is recorded as this y_{2a} and the former y_a. After that y_a is changed for a different value and the process above is repeated to get another v_g. From these group velocities with different y_a, the minimum v_g is chosen and is recorded as its y_d, y_a and y_{2a}. This v_g is the minimum value in the cases with the same y_d and different y_a and y_{2a}. Afterwards y_d is changed for a different value and the steps above are repeated. The minimum of group velocities for different y_d are got.

In the simulation, several sets of data are calculated. Though most of the group velocities are larger than 0.01c, it is found that when $y_d = 0.29a$, $y_a = -0.01a$ and $y_{2a} = 0.01a$, the group velocity of the guided band is decreased to 0.0096c and the group index n_g equals 104. To make the crystal operate at the wavelength of 1550 nm, the lattice constant a is set as 620 nm. The bandwidth of the guided band is 0.000781 in terms of the normalized frequency $\omega a/2\pi c$, which equals 3.0 nm (0.2% of the central wavelength).

3. Conclusions

In summary, a wide bandwidth and low velocity can be achieved by tuning the position of the defect row, the first and second rows adjacent to the defect row. We numerically demonstrate that by increasing y_d, y_a or y_{2a}, the group velocity can be decreased and fine tuning of these three parameters can produce a relatively broad bandwidth of the guided band. Besides it is found that when $y_d = 0.30a$, $y_a = 0a$, $y_{2a} = 0a$, and $y_d = 0a$, $y_a = -0.17a$, $y_{2a} = 0a$, there are inflection points in the calculated v_g–y_d and v_g–y_a figures respectively. By tailoring these three parameters we finally get a group velocity of 0.0096c and 3.0 nm bandwidth with $y_d = 0.29a$, $y_a = -0.01a$ and $y_{2a} = 0.01a$. The results are of reference value for designing low group velocity and wideband structures based on PhCW.

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