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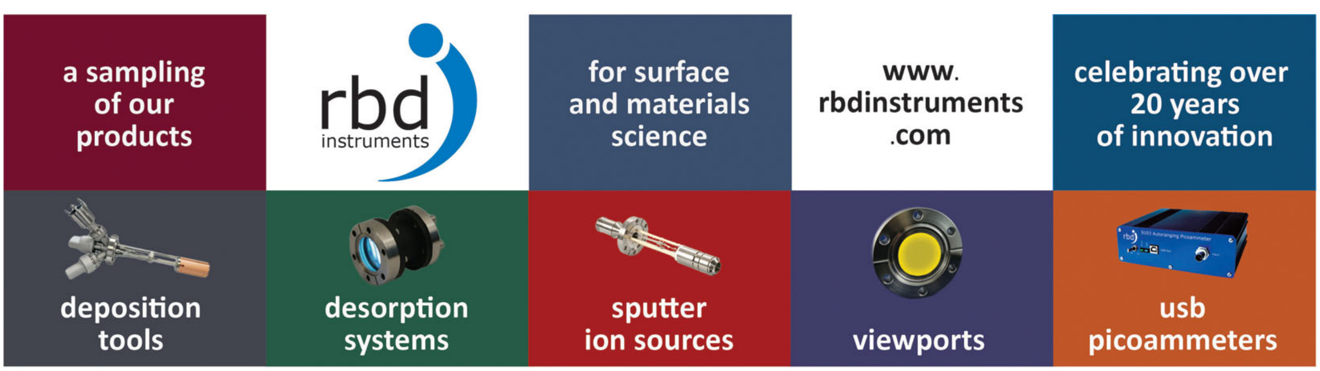

Zero dispersion at small group velocities in photonic crystal waveguides

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Modes of photonic crystal (PC) line-defect waveguides can have small group velocity away from the Brillouin zone edge. This property can be explained by the strong interaction of the modes with the bulk PC. An anticrossing of "index guided" and "gap guided" modes should be taken into account. To control dispersion, the anticrossing point can be shifted by the change of the PC waveguide parameters. An example of a waveguide is presented with vanishing second- and third-order dispersion. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1815066]

Photonic crystals (PCs) can be used as omnidirectional mirrors to confine light inside defect channel waveguides.[1,2] These waveguides are often considered as ultrasmall optical guides and interconnects, with a stress on large bandwidths, large group velocities,[3,4] and small bend losses.[5] But, small group velocity in PC waveguides is also an interesting issue. For instance, microphotonic sensors, integrated laser amplifiers, and devices based on nonlinear optical interactions will profit from strong light matter interactions due to small group velocities and dispersionless pulse propagation. PC waveguides were already proven to exhibit small group velocities down to $v_g=0.02c$.[6] To utilize these properties, long waveguides are needed where scattering losses can be substantial, but recent results give an optimistic value of approximately 1 dB/mm.[6,7] Small group velocities near the band edge are observed in any waveguide with periodical corrugation, though the unavoidable group velocity dispersion is present. Thus, optical signals propagating through such waveguides will be strongly distorted. In this letter, we have examined PC defect waveguide modes and revealed the possibility to control the dispersion at small group velocities. We will mostly concentrate on obtaining a dispersionless waveguide, though this approach can be also used to achieve high quasi-constant dispersion and, therefore, can be applied to the compensation of the chromatic dispersion of optical fibers. There are also coupled cavities waveguides,[8,9] where constant small group velocities are obtained. However, in slab waveguides,[10] coupled cavity modes will lie above the light line and will thus exhibit high intrinsic losses.

Si air–bridge structures with the triangular lattice of holes are considered, where a is the lattice constant, r is the radius of the holes, $n=3.5$ is the slab refractive index, and $h=0.5a$ is the thickness of the slab. The vertical component of the magnetic field is used to define the symmetry of the modes. Only vertically even, transverse electriclike modes are discussed, where hole slabs have photonic band gaps (PBGs). A line-defect waveguide is formed by leaving out a row of holes in the ΓK direction and shifting the boundaries together, where the width is defined as the percentage of $W=\sqrt{3}a$. The modes of such waveguides at frequencies inside the PBG can be categorized with respect to their field distribution as "index guided" or "gap guided."[3] An index guided mode has its energy concentrated inside the defect and interacts only with the first row of holes adjacent to the defect. Its behavior can be simply represented by a dielectric waveguide with periodical corrugation.[11] A gap guided mode interacts with several rows of holes, thus it is dependent on the symmetry of the PC and its PBG. The terms index guided and gap guided do not exactly specify the guidance mechanisms (in the PBG region, all modes are gap guided) but mainly describe the modal field distribution.

An index guided mode generally shows a small group velocity near the band edge which eventually vanishes at the Brillouin zone edge. A simple parabolic approximation can be considered:

$$\omega \approx \left(\frac{\Delta k}{\alpha}\right)^2 + \omega_0,$$

where ω is the mode frequency, ω_0 is the mode frequency at the Brillouin zone edge, Δk is the wave vector difference to its value at the Brillouin zone edge, and α is a function of the corrugation strength and depends mostly on the index contrast and the hole radii. The stronger the corrugation, the flatter the mode near the band edge. The first derivative over the wave vector is the group velocity:

$$v_g = \frac{d\omega}{dk} \sim \frac{\Delta k}{\alpha^2} \sim \frac{(\omega-\omega_0)^{1/2}}{\alpha},$$

the second derivative over the frequency is the dispersion:

$$D \sim \frac{d(1/v_g)}{d\omega} \sim \frac{\alpha}{(\omega-\omega_0)^{3/2}} \sim \frac{1}{\alpha^2 v_g^3}.$$

So, the stronger the corrugation, the smaller the dispersion at the same group velocity. In any case, the cubic dependency on the inverse group velocity makes the application of small group velocities difficult due to the large signal distortion.

Gap guided modes show a much more complicated behavior. Due to the introduction of the linear defect in the triangular lattice, the edge of the Brillouin zone is shifted to the K' point (Fig. 1). Thus, the M point is folded back to the Γ point, and the K point appears between the Γ and K' points. Group velocity can vanish also at the folded K point. A laterally odd mode (with respect to a plane along the propagation direction and vertical to the slab) has a node in the center of the PC defect waveguide and most of its energy is located in the PC lattice. Thus, this mode is similar to the folded bulk PC mode from K' to M points with a maximum at the folded K point. Between the folded K and K' points, one observes negative group velocity (positive group veloc-

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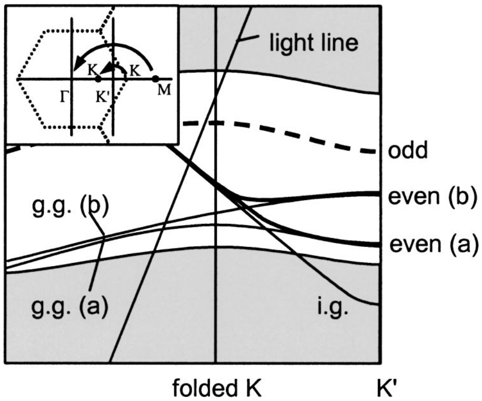

FIG. 1. Schematic band structure of triangular lattice PC line-defect waveguide, vertically even modes. Appearance of the folded K point is shown in the inset. The laterally odd mode has negative slope between the folded K and K' points. The laterally even mode is formed as an anticrossing of index guided and gap guided modes. Two cases are possible: (a) Gap guided mode has negative slope and PC mode has monotonous dependency; and (b) gap guided mode has positive slope and PC mode can have nonmonotonous dependency with two wave vectors for one frequency. To be truly guided, all modes should stay below the light line.

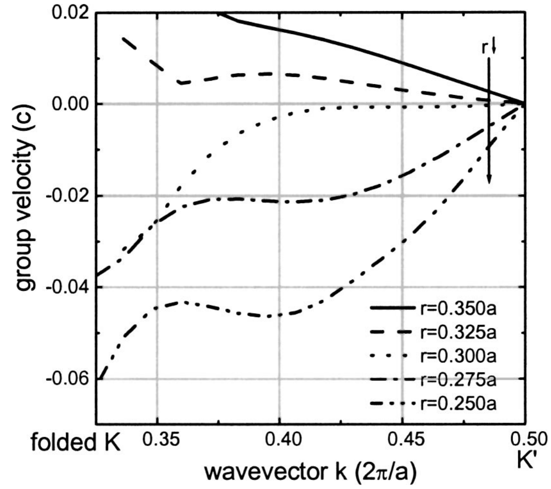

FIG. 3. Group velocity as a function of a wavevector for the even W0.7 waveguide mode with different radii of the holes. For large radii, the gap guided mode has positive group velocity. As the radius decreases, the group velocity becomes negative. A breaking point appears at $r=0.3a$.

ity in the unfolded band diagram) and a point of zero dispersion. But a laterally odd mode is difficult to couple with a monomode dielectric waveguide due to the symmetry mismatch. Thus, later we will concentrate on laterally even modes.

There is an intrinsic interaction of even gap guided and index guided modes (Fig. 1).[3] This interaction forms two supermodes, which are represented by the sum of gap guided and index guided modes in phase and in antiphase. Due to the fast change of group velocity at the anticrossing point, the group velocity dispersion has a maximum there. This effect is very similar to the coupled waveguides approach for dispersion compensation,[12,13] except that here two modes from the same waveguide couple. An example of the band diagram, group velocity, and dispersion at the intersection point is shown in Fig. 2. A three-dimensional finite integration frequency domain eigenmode solver was used to find the band diagram of a rectangular supercell. The supercell is formed by 4a high air claddings and 4 W long PC lattice on both sides of the defect.

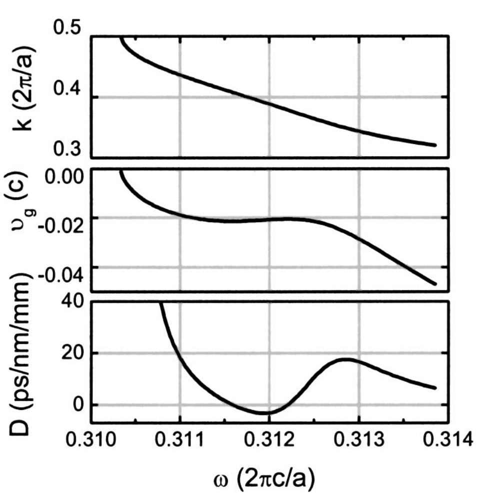

FIG. 2. The wave vector, group velocity, and group velocity dispersion of the PC waveguide as functions of frequency ($r=0.275a$, $h=0.5a$, W0.7, and air bridge $n=3.5$). Normalized frequency is used, $a=465$ nm corresponds approximately to 200 THz mode frequency (1500 nm wavelength). Group velocity $-0.02c$ has a bandwidth of constant value (approximately 1 THz), dispersion is almost zero throughout this bandwidth.

A maximum of the group velocity dispersion can be achieved only if two intersecting modes have the same sign of group velocity [mode even—in Fig. 1(a)], otherwise the so-called ministopband is formed, and dispersion diverges the same as at the Brillouin zone edge [mode even—in Fig. 1(b)]. In our case, the folded branch of index guided mode has negative group velocity. Thus, it is important to obtain negative group velocity of the gap guided mode too. Here, we return to the important issue of the PC symmetry. As was already discussed, the odd gap guided mode, which interacts strongly with the PC, has maximum at the folded K point and a negative group velocity between the folded K and K' points. The even gap guided mode concentrates most of its energy in the unstructured part of the waveguide. The strength of the PC, namely the radius of the holes, becomes important. The weaker the PC the deeper the even gap guided mode penetrates into the PC and the stronger it feels the two-dimensional (2D) periodicity. Depending on the radii of the holes, the group velocity between folded K and K' points can change from positive to negative (Fig. 3). The radius $r=0.3a$ is the value that leads to a very flat gap guided mode between the K and K' points with group velocity almost zero. It should be mentioned that the anticrossing with the index guided mode cannot be avoided and can be seen in Fig. 3. However, the mode near the Brillouin zone edge is away from the anticrossing point and has the property of the original gap guided mode.

The W0.7 waveguide is used in the previous examples. This value has been derived as an approximately optimized value to achieve a quasi-flat group velocity. A decrease of the waveguide width moves up both the gap guided and index guided modes in the band diagram. However, the gap guided mode moves faster. Thus, the anticrossing point shifts to smaller wave numbers (Fig. 4). The gap guided mode alone would have a maximum of its group velocity value somewhere between the folded K and K' points. In the W1 waveguide the anticrossing takes place before this maximum is achieved. By shifting the anticrossing point to the left, a maximum of group velocity can be obtained. The group velocity dispersion is zero there. The anticrossing can be ad-

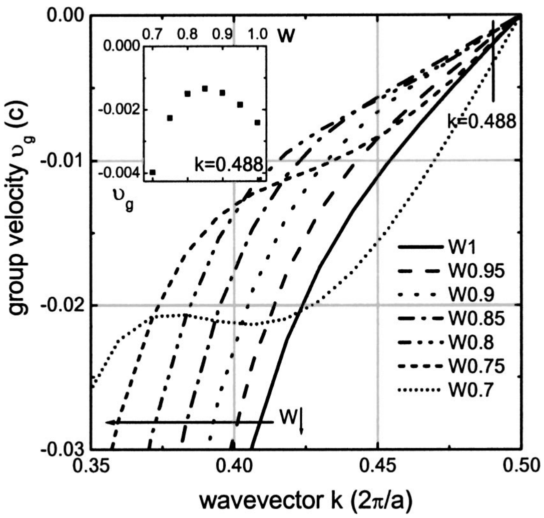

FIG. 4. Group velocity as a function of a wave vector for $r=0.275a$ with different waveguide widths. The inset shows group velocity at the $k=0.488$ point, absolute value of group velocity has minimum at W0.85. The point of anticrossing with the index guided mode, when absolute value of group velocity starts to increase dramatically, shifts gradually to the left with decreasing waveguide width. A bandwidth of constant group velocity is obtained at W0.7.

justed in a way that even the third-order dispersion is zero (approximately at W0.7), and thus the bandwidth of constant group velocity is increased. The depth of light penetration into the PC also changes with the waveguide width due to the shift in frequency. W1 and W0.7 waveguides has even modes near the upper and lower edges of the PBG, where the penetration depth is large. Thus, the gap guided modes follow the symmetry and exhibit quite large negative group velocity (see inset of Fig. 4). In the middle of the PBG (W0.85), penetration depth is smaller and the group velocity absolute value is decreasing.

Thus, by simple variation of the holes radii and the waveguide width in Si air–bridge structures, it is possible to obtain a bandwidth (1 THz) of quasi-constant group velocity ($0.02c$). The high index contrast—like in the material system Si/air—and the vertical symmetry—as achieved in air–bridge structures—are compulsory for the discussed applications. Only in this case, the mode with constant group velocity stays below the light line throughout the whole bandwidth. The hole radii should be smaller than $0.3a$, otherwise a bistable mode is formed, which at the same frequency has two states—index-guide and gap guided. There will be a problem to couple from a conventional waveguide mode into the gap guided mode, because due to the impedance match most of the energy will couple to the index guided mode. In the case of radii smaller than $0.3a$, the mode has a monotonous behavior and adiabatic coupling can be applied.[14] The mode of a dielectric waveguide can be coupled to the index guided mode of the slightly detuned PC waveguide, which then can be adiabatically changed on the scale of several lattice constants to guide the mode in the bandwidth of constant group velocity. Several parameters can be gradually changed: Width of the waveguide, radius of the holes, and index and thickness of the slab.

In conclusion, we have thoroughly investigated the group velocity dispersion of PC defect waveguide in a triangular lattice slab. The importance of the PC 2D symmetry on the waveguide properties was shown. The influence of the penetration depth on the group velocity was demonstrated, where the penetration depth was controlled by the radii of the holes. It was shown that a simple PC waveguide, with altered waveguide width W0.7, offers enough degrees of freedom to achieve a 1 THz bandwidth of constant group velocity $0.02c$ with vanishing second- and third-order dispersion. We have introduced an approach to explain the dispersion relation of PC waveguide and how it can be modified. In this letter, we considered the most simple case, namely the width change, which is also favorable for manufacturing. However, the same approach can be applied to more complicated designs as, for example, the change of holes adjacent to the waveguide, which will be considered elsewhere.

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