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Study on transmission of photonic crystal waveguide with slow light phenomena

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ABSTRACT

In this paper, we propose the transmission properties of three two-dimensional photonic crystal waveguides (PCWs) obtained by shifting the shape of air holes localized at each side of the waveguide using the finite difference time domain (FDTD) method. One modifies the radius of air holes and the permittivity of dielectric rods which replace air holes. The other substitute air rings for air holes. The last one is combination of air rings and air holes or dielectric rods. We show that we can achieve unusual "Γ-type" or "n-type" transmission spectrum depending on the different parameters such as thickness of air holes, inner radius of air rings and permittivity of square dielectric rod. The notable difference is presented to different structures. Furthermore, we show the slow light phenomena using a unique geometrical parameter. This work will be of significance in fabricating PC devices.

1. Introduction

During the last two decades, two-dimensional (2D) planar photonic crystals (PCs) [1,2] have attracted a lot of attention due to their unique characteristics for light propagation and ease of fabrication, using mature semiconductor fabrication techniques. Conventional 2D planar PC structures are implemented by etching a periodic array of air holes in a dielectric slab, e.g., silicon. In these structures, photonic crystal waveguides (PCWs) are typically formed by removing the central row of holes/rods of a perfect PC slab [3–5]. A unique feature of these PCWs is the existence of slow group velocity modes [6,7], which does not occur in non-periodic waveguides.

Slow light phenomena in integrated photonics are envisioned to bring reduction of device sizes and power consumption, enhance light-matter interactions, and thus bring solutions for optical integrated circuits [8]. Thus, slow light is the hotspot in the domain of optical communication. The most commonly used slow light device in PCs is the so-called W1 waveguide. However, large group index in W1 waveguides is only obtained in extremely narrow bandwidth and large group velocity dispersion effects accompany the slow light regime, which causes large signal distortion in the time domain.

So far, two main approaches have been proposed to eliminate the drawbacks due to dispersion and obtain slow light in PC waveguides. The first one relies on dispersion compensation by chirping the PC properties [9,10]. The other one is based on nearly zero dispersion by adjusting the PC geometry, including changing the hole size [11] or hole position of the first two rows [12], and using annular holes for the whole lattice [13] or only the first line [14,15].

With respect to the last solutions, we present in this paper a novel, simpler, and more flexible way to adjust the PC waveguide geometry, leading to a larger bandwidth dependence of transmission properties curves as a function of normalized frequency.

2. The basic theories

In this paper, the non-loss and non-magnetic material was chosen. The time dependent Maxwell's equations in PCWs can be written in the following form,

$$\frac{\partial \vec{E}}{\partial t} = \frac{1}{\varepsilon(\vec{r})} \cdot \nabla \times \vec{H} \quad (1)$$

$$\frac{\partial \vec{H}}{\partial t} = -\frac{1}{\mu(\vec{r})} \cdot \nabla \times \vec{E} \quad (2)$$

where $\varepsilon(\vec{r})$ is the position dependent permittivity and $\mu(\vec{r}) = \mu_0$ is permeability in vacuum. In a 2D case, the fields can be decoupled into two transversely polarized modes, namely, the TE mode and the TM mode. These equations can be discretized in space and time by a so called Yee-cell technique [16]. The following FDTD time stepping formulas are the spatial and time discretizations of

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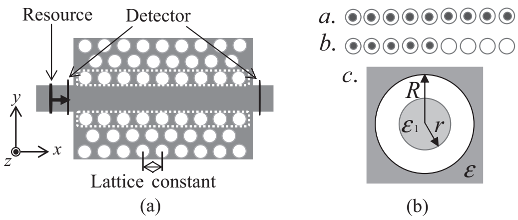

Fig. 1. (a) Simulation structure indicating the PCW, (b) *a*. A row of air rings. *b*. A row of air rings combined with air holes. *c*. Schematic picture of the proposed air ring geometry.

Eqs. (1) and (2) on a discrete 2D mesh within the *x*–*y* coordinate system for the TE mode.

$$E_x|_{n+1}^{i,j} = E_x|_n^{i,j} + \frac{\Delta t}{\varepsilon_{i,j}} \cdot \frac{H_z|_{n+1/2}^{i,j+1/2} - H_z|_{n+1/2}^{i,j-1/2}}{\Delta y} \tag{3}$$

$$E_y|_{n+1}^{i,j} = E_y|_n^{i,j} + \frac{\Delta t}{\varepsilon_{i,j}} \cdot \frac{H_z|_{n+1/2}^{i+1/2,j} - H_z|_{n+1/2}^{i-1/2,j}}{\Delta x} \tag{4}$$

$$H_z|_{n+1/2}^{i,j} = H_z|_{n-1/2}^{i,j} + \frac{\Delta t}{\mu_0} \cdot \left(\frac{E_x|_n^{i,j+1/2} - E_x|_n^{i,j-1/2}}{\Delta y} - \frac{E_y|_n^{i+1/2,j} - E_y|_n^{i-1/2,j}}{\Delta x} \right) \tag{5}$$

where the index *n* denotes the discrete time step, indices *i* and *j* denote the discretized grid point in the *x*–*y* plane, respectively. Δt is the time increment, and Δx and Δy are the intervals between two neighboring grid points along the *x* and *y* directions, respectively. Similar equations for the TM mode can be easily obtained. One can easily see that the computational time is proportional to the number of discrete points in the computation domain for a fixed total number of time steps.

In calculation, the time increment Δt and the space intervals Δx and Δy are satisfy numerical stability condition

$$\Delta t = \frac{0.95}{c} \left(\frac{1}{(\Delta x)^2} + \frac{1}{(\Delta y)^2} \right)^{-1/2} \tag{6}$$

where *c* is the speed of light in vacuum.

3. Waveguide geometry

Fig. 1(a) shows a 2D PCW structure in a triangular lattice PC of air holes (with radius *R*) in In/GaInAsP. The dielectric constants of air and In/GaInAsP are named as $\varepsilon_0 = 1.0$ and $\varepsilon = 10.5$, respectively. To simplify the simulation, we have used the normalized lattice constant which is denoted as *a*. The radius of air holes is $R = 0.36a$ to ensure maximum photonic bandgap for TE modes. The line defect waveguide is created by missing a row of holes in the center along the *x*-direction; this is the so-called W1 waveguide and it has been investigated extensively before [17]. Differently, we use the following three modes to take the place of the rows of air holes closest to the line defect waveguide and the other rows keep unchanged. The first mode is the thinner air holes, the second one is air rings, and the third one is the combination of air rings and air holes. Thus, the modified PCW system can be obtained. In Fig. 1(b), *a* represents the second mode, *b* indicates the third mode, and *c* denotes the air ring with inner radius *r* and outer radius *R* and the permittivity of the homocentric dielectric rod is defined as ε_1 which is adjustable. We focus our attention on TE modes, which have magnetic fields parallel to the *z*-axis. Special consideration should be given at the boundary of the finite computational domain, where the fields are updated using special boundary conditions as information out of the domain is not available. Here, the perfectly matched layer (PML) method is used for the boundary treatment.

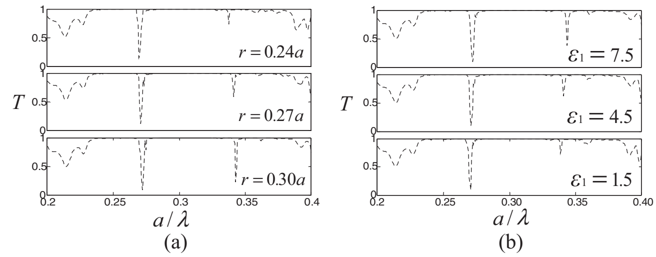

Fig. 2. Dependence of transmission spectrum on (a) air holes radius *r* and (b) permittivity of dielectric rods.

For our simulation, lattice period (*a*) is equal to 24 FDTD grid points. To calculate PCW power transmission spectrum, we used pulsed waveguide source to excite the fundamental TE mode. The spectrum of powered transmitted through the PCW is calculated by taking the Fourier transform of the fields and integrating the Poynting vector over a surface of 141 grid points, centered at the middle of output PCW. And then the power transmission spectrum is calculated as the ratio of the power transmitted through the PCW to the power transmitted through a similar waveguide structure of equal length. The thickness of the perfectly matched layer is set to 12 grid points.

4. Results and discussion

The transmission characteristics of the PCW are related with many factors such as the periodic structure, the filling ratio, the dielectric constant of materials, and so on. In this paper, we concentrate on that the influencing of the thickness of air holes or inserted rods with the dielectric constant on the transmission properties. This is of more interest for integrated optics applications. In order to obtain the most affection of the above parameters on the transitivity of PCW, firstly, changing the size of air holes closet to the line defect, surrounded by the dashed lines and shown in Fig. 1(a). In our simulation results, *x*-axis denotes normalized frequency (a/λ) and *y*-axis represents normalized transmission coefficient, named as ***T***. The calculated results are shown in Fig. 2(a). The radius of air holes changed thinner is denoted as *r*. From the result we observe that the transmission spectrum keep the same with each other in the frequency range from 0.24 to 0.38 except the position of $a/\lambda = 0.34$ approximately, differently, the transmission coefficient becomes smaller with the decreasing of *r*. This is because that the group velocities increase and backscattering loss becomes very little with the decreasing of *r*.

Secondly, we substitute the air holes for dielectric rods. The transmission spectrum is shown in Fig. 1(b). It is revealed that the transmission coefficient becomes large with the decreasing of dielectric constant of dielectric rod at the frequency position of $a/\lambda = 0.34$. From Fig. 2(a) and (b), it is concluded that the transmission properties of the air holes with $r = 0.24a$ is the same with the one of dielectric rod with $R = 0.36a$ and $\varepsilon_1 = 1.5$. So, people can choose from the above two ways to satisfy the practical requirement. Also, the wider and flatter transmission band can be obtained by reducing the radius and dielectric constant of dielectric rods, simultaneously.

The second mode is that we employ air rings to take the place of air holes shown in Fig. 1(b) *a*. The detailed results by changing the value of inner radius of air rings and dielectric constant of dielectric rods with $r = 0.3a$ are presented in Fig. 3(a) and (b), respectively. The shape of the transmission spectrum in the two cases is reasonably similar comparing with the results displayed in Fig. 2. But transmission spectrum becomes wider and flatter.