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Waveguiding Effect in GaAs 2D Hexagonal Photonic Crystal Tiling

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In this paper we theoretically study (with plane wave expansion and finite-difference time-domain models) waveguiding effect of the 2D hexagonal dielectric photonic crystal tiling. The structure is made of GaAs dielectric rods in air. We perform the calculations of the band structures, equi-frequency contours and electromagnetic propagation through the new type of the photonic crystal and self-collimation waveguides making it possible for application.

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1. Introduction

Photonic crystals (PC) are artificial structures that have a periodic dielectric constant. They are designed to control photons in the same way that crystals in solids control electrons. Some specific PC possess energy ranges, called the photonic band gap (PBG), where light propagation is completely prohibited. If linear defects are introduced in such PC, light propagation can be completely guided along a path of the linear defects, in what is called a PC waveguide (PCW), even when it largely bends. PCW advantages are low losses, high confinement and the fact that they can be fabricated in actual materials already used in electronic industry.

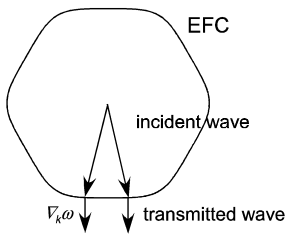

Fig. 1. Illustration of the self-collimation phenomena for an EFC. $\nabla_k \omega$ is the group velocity.

Also, it is well known that for specific frequencies and PC lattices light can propagate without diffraction, which can leads to the phenomenon that is of the special interests of our research in this paper, self-collimation (for some authors self-collimation is also known as super--collimation) [1–3]. The self-collimation effect relies on the special dispersion properties of the Bloch waves in PC, where the curvature of the equifrequency contours (EFC) departs from the normally circular curvature in free space. As the direction of a propagating Bloch mode is always normal to the EFC, the self-collimation is achieved when they are as flat as possible (Fig. 1). Self-collimation, also known as auto-collimation or self--guiding allows a narrow beam to propagate in the photonic crystal without any significant broadening or change in the beam profile, and without relying on the light intensity, bandgap or engineered defects, such as waveguides (advantage over the PCW). This property can be used for waveguiding and dense routing of optical signals.

2. Structure

We analysed the structure which belongs to class of the Archimedean lattices [4] (Fig. 2) and by notation of Grünbaum and Shephard [5] is named by $(3, 12^2)$. In contrast to our previous work with square Archimedean lattices [6, 7] this structure falls in the hexagonal crystal system with the $P6mm$ plane symmetry group according to the *International Tables for Crystallography* [8]. The primitive unit cell and the first Brillouin zone with symmetry points are presented in Fig. 2. It has 6 atoms per unit cell. Structural motiv is dodecagon which is placed in the structure like hexagonal lattice.

3. Results

In this paper we present research of the waveguide effect (by the self-collimation and the presence of PBG)

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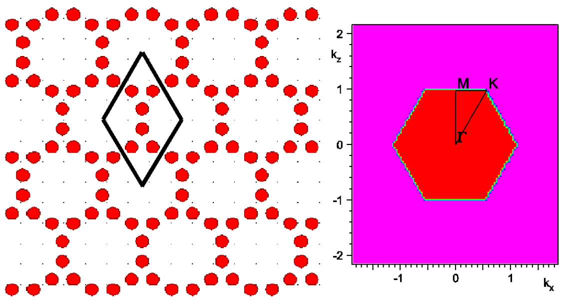

Fig. 2. Crystal lattice, primitive unit cell and the first Brillouin zone with symmetry points of the (3, 12^2).

in the PC lattice which is made of the GaAs 2D dielectric cylinders ($\varepsilon = 12.96$) in air ($r/a = 0.48$, where r is the rod radius and a is smallest distance between the rods). Also, it is assumed that material is homogeneous, linear and lossless. As a tool for the analysis we used RSOFT [9] to calculate band structures, EFC and for the wave propagation through PC. The theoretical models are well known plane wave expansion (PWE) method for the first two calculations and a finite-difference time-domain (FDTD) method for the latter.

In Fig. 3a there is presented the band structure (obtained with PWE model) of the first five bands, TE/TM polarization (TE and TM polarizations means that electric and magnetic field vectors are normal to the plane of the wave propagation, respectively) and $r/a = 0.48$ (the rods almost touch). From this picture, one can see wide gap for TM polarization that emerges between first and the second TM band for normalization frequency range $\bar{f}$ $(= \omega a/2\pi c) = 0.085$–$0.121$. For these frequencies, there is no propagation of the light in material which leads to waveguiding effect in PCW structures [10].

As the application of the (3, 12^2) lattice we construct a PCW. The PCW is formed by removing two rows of dodecagons from the original structure which creates line defect (Fig. 3b). The dimensions of this structure with the M interface are $37a \times 42.5a$. The FDTD model simulates propagation of the wave through the line defect. For the wide continuous Gaussian beam, band gap frequency ($\bar{f} = 0.1$, $\lambda/a = 10$) and TM polarization we obtained clear guiding without losses.

The next phenomenon which we study in (3, 12^2) structure, as suitable for application in guiding waves, is self-collimation. To find propagation direction of the light through the PC, with PWE model, we analyze EFC for different bands and polarizations. The results are presented in Fig. 4 for the TE2 band. According to appropriate interface of the structure, full normal and parallel line are normal and parallel component of k wave vector. The parallel component of k is conserved in refraction (the Snell law). The first Brillouin zone of (3, 12^2) lattice is shown by the broken line. The symmetry points, Γ, K and M of the first Brillouin zone are also marked.

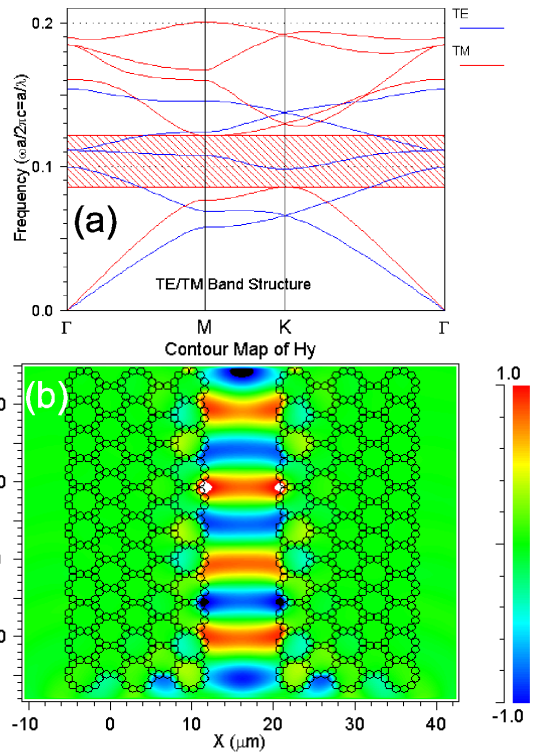

Fig. 3. (a) Band structure of the first five bands, $r/a = 0.48$ and TE/TM polarization. (b) Propagation of wave through the PCW for the band gap frequency $\bar{f} = 0.1$ ($\lambda/a = 10$) and TM polarization.

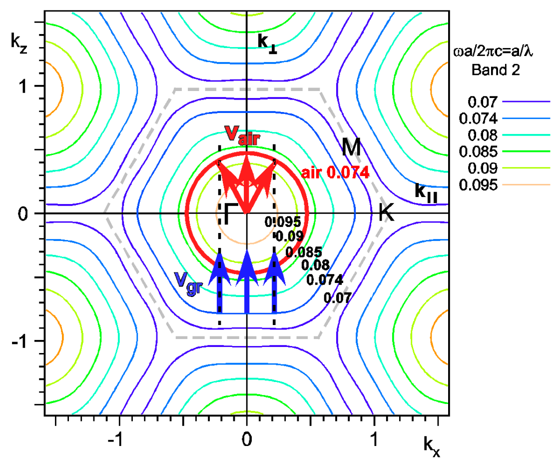

Fig. 4. The EFC plot for the TE2 band and the $r/a = 0.48$. The orange circle and upper arrows indicate incident air wave ($\bar{f} = 0.074$, $\lambda/a = 13.51$) in the range of angles (0–28°). For these conditions, part of the corresponding PC EFC is virtually straight (almost flat) and the group velocities are almost the same (lower arrows). This is the reason for the self-collimation effect to emerge.

From the figure one can see that contures are very flat for the frequencies near the end of the first Brilloiun zone and around M symmetry point (necessary condition for the self-collimation effect). We can predict that the self--collimation effect will emerge for $\bar{f} = 0.07$–0.08. To confirm that assumption, we construct an air frequency contour for frequency $\bar{f} = 0.074$ ($\lambda/a = 13.51$) to find the directions of the group velocity (to tell us about wave propagation) in PC. For that frequency, incident angles up to 28° (0–28°) and from the well known formula, for group velocity, $\boldsymbol{v}_{\rm g} = \nabla_k \omega$ we concluded that transmitted wave inside the PC will propagate without dispersion (the refracted angle is almost zero). For $k_x = 0$ ($\theta_{\rm in} = 0°$) we find flatness EFC (the curvature of the couture is extremely small) which is fundamental for good collimation and application. For the flattest EFC the beam is traveling to longest distances without dispersion (so-called super-collimation [2]). Similar situation emerges in the TM2 band.

In order to confirm the self-collimation effect made by analysis of the EFC, we analyzed, with FDTD model, propagation of the wave through the $(3, 12^2)$ structure. The structure, which we call self-collimation waveguide (SCW), as potential application for integrated optic devices, is made of the 21 layers of dodecagons with K interface. The dimensions of the structure are $42a \times 69.5a$ which is small enough for integrated optical circuits and also large enough for good guiding of wave. For best performances (long dispersionless propagated beam), parameters for simulation of the continuous Gaussian incident wave are $\bar{f} = 0.074$ ($\lambda/a = 13.51$) and $\theta_{\rm in} = 0°$. The results are presented in Fig. 5. As we predicted in the EFC analysis we got clear self-collimation inside the structure even for the oblique incidence. The wave inside the PC propagates without dispersion.

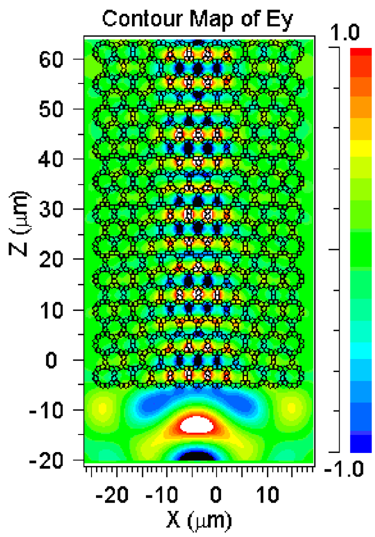

Fig. 5. Propagation of the self-collimated TE beam through $(3, 12^2)$ structure without dispersion. Incident wave parameters are $\bar{f} = 0.074$ ($\lambda/a = 13.51$) and $\theta_{\rm in} = 0°$.

Also, from the figure, one can see that for this interface major part of the field is located in the walls made of dielectric cylinders which can be desirable for good waveguiding. To fit operating wavelength at 1.55 μm (telecommunication wavelength) the lattice constant and the radius of the dielectric rods must be $a = 0.115$ μm and $r = 0.055$ μm.

4. Conclusions

In this paper, we present our research of the waveguiding effect in the less known 2D hexagonal lattice tiling made by dielectric GaAs rods in air. We investigated possibilities of the waveguiding effect for applications of the $(3, 12^2)$ Archimedean PC lattice. We propose the new type of the PCW and SCW devices for integrated optics applications based on the PBG and self-collimation effect, respectively.

Acknowledgments

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