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Photonic crystals with defects, as a storage location for cooling atoms and ions

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Photonic crystal structures with defects for the localization of light are considered in this paper. The simulation of the radiation field inside the photonic crystals with defects is calculated. Accommodation and cooled storage of atoms or ions within the defect are given is well.
Keywords: photonic crystals, localization of light, point defects, linear elements, planar waveguides, electromagnetic field, Maxwell's equations, photonic band gaps, finite-difference time-domain method, plane wave expansion method.

В данной работе были рассмотрены фотонно-кристаллические структуры с дефектами для локализации света, был проведен расчет и симуляция поля излучения внутри фотонных кристаллов с дефектами. Приведены условия размещения и хранения охлажденных атомов или ионов внутри дефекта.
Ключові слова: фотонні кристали, локалізація світла, точечні дефекти, лінійні елементи, плоскі волноводи, електромагнітне поле, рівняння Максвелла, фотонна заборонена зона, метод кінцевих різниць у часовій області, метод розширення плоскої хвилі.

У даній роботі були розглянуті фотонно-кристалічні структури з дефектами для локалізації світла, був проведений розрахунок і симуляція поля випромінювання всередині фотонних кристалів з дефектами. Наведено умови розміщення та зберігання охолоджених атомів або іонів всередині дефекту.
Ключові слова: фотонні кристали, локалізація світла, точечні дефекти, лінійні елементи, плоскі волноводи, електромагнітне поле, рівняння Максвелла, фотонна заборонена зона, метод кінцевих різниць у часовій області, метод розширення плоскої хвилі.

Introduction

Photonic crystal structures [1, 2] have become one of the main themes in the last decade which presented much interest in nanophotonics. The applications in the area of nanophotonics due to the large number of studies about photonic crystals have been formed.

Photonic crystals represent an important and necessary element for the realization of light waves control functions in areas such as quantum optics, telecommunications, lasers and biomedical engineering. These structures can be used to construct the resonators, the size of which may be comparable with the order of the wavelength of light. These resonators can facilitate the interaction of light with matter, as a result of quantum-optical phenomena, such as the increase in spontaneous emission [3], strengthening the connection [4], and hold the atoms in the cavity [5].

The aim of this research is to determine the distribution of the electromagnetic field intensity in the crystal defect, which will allow due the gradient field intensity forces hold atoms and ions in the center of the defect.

The problem which is solved in this case by using defect in the photonic crystal associated with the creation of frequency reference points which are necessary for frequency stabilization of the laser radiation sources. In this article we have presented the results of analysis photonic crystals with defects in the form of a usual linear resonator and a T-shaped resonator.

Defects of photonic crystals and light localization

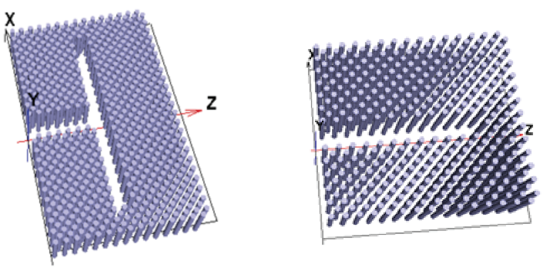
One of the most important properties of photonic crystals is the localization of light. It occurs when photons enter into the photonic medium and become locked or localized in it. First Anderson and Mott studied and observed electron localization in disordered solids [6]. However, the theoretical predictions are often met with difficulties in registered experimental data because of the existence of the electron-electron interactions and electron-phonon interaction. S. John first explored the possibility of observation of localized light states in a dielectric medium [7]. The experiments were carried out which quickly verified the existence of weak localization in the form of coherent backscattering [8-10].

However, there was important problem: the effective energy of the wave equation of light in an inhomogeneous medium is always positive, and the photon energy is always higher than the potential barriers for the realization of strong localization of light [11]. After Yablonovich first has proposed the three-dimensional structure of dielectric photonic crystal with band gaps, John made conclusions [12] that moderate disorder disturbance of this structure could lead to the observation of the strong localization of light.

The localization of light in the photonic crystals occurs via introduction of certain defects in the crystal structure of a photonic crystal. There are major variations of introduced defects such as point defects, when in the structure one element is deleted or changed; or linear elements (figure 1) when a series of photonic crystal structures was removed or modified. While photons with energies within a photonic band gap cannot propagate through the crystal, they may be limited in the defective areas. Light with a frequency within the band gap may be distributed along the channel defect because it is reflected from the walls of the defect. It is also possible to use the point defects in photonic crystals of light like traps, when the photons are held in the place of point defect. The photonic crystal fibers and traps have a great practical importance for miniature optoelectronic circuits and devices [13].

Numerical research defects in photonic crystals

If we consider the planar waveguides created on the basis of two-dimensional photonic crystal in which it is possible to form a linear defect and so limit the light that it may extend only along a predetermined trajectory. In this case the lack of one or more rows of rods or holes should be understood by linear defect.



a *b*

Fig. 1. Photonic crystals with linear defects: a - T-shape waveguide; b - linear waveguide.

If through this defect we let the light flow with coincide with the frequency of band gape of the photonic structures, it will be limit by the defect and spread strictly along it. This allows manipulating the traffic light, turning its trajectory at large angles up to 90 °, on the micron scale. This scattering loss will be completely eliminated.

The difference between the photonic crystal waveguide by ordinary coaxial waveguide consists in the possibility rapidly change of the direction of light propagation without great losses. Another advantage of such a waveguide is that if a defect is a region free from the substance, the light propagates in the waveguide preferentially in air, and thus the absorption and dispersion effects are greatly reduced.

The localization of the electromagnetic field is one of the important properties of structures with photonic band gaps. The challenging and transmission light in a photonic-crystal waveguide is possible at different angles and rotations of the waveguide.

The perspective field for the distribution of research in the photonic crystals is a method that is based on the numerical solution of Maxwell's equations, which is called the finite difference method (FDTD) [14]. In this paper we applied FDTD method to analyze the localization and the channeling the electromagnetic field in a two-dimensional photonic crystal structure with a lattice defect. By using this method it is possible to draw important conclusions from the physical and technical point of view about the nature of radiation channeling in defect photonic crystals. Our analysis in this paper demonstrates that the electromagnetic field in these conditions can be localized in the region smaller than the wavelength in the band gap of the photonic crystal.

In this paper two structures, which represented two dimensional photonic crystals have been studied, which are the periodic structure of cylindrical rods, arrange hexagonally and surrounds by air. The defects are created by removing several rows of rods to produce a T-shaped waveguide and an ordinary waveguide.

The simulation results of the optical propagation in two-dimensional photonic crystal are analyzed by OptiFDTD software.

The mathematical basis of the method of numerical simulation

We used Finite-difference time-domain method (FDTD) and method plane wave expansion (PWE) to analyze the photonic crystal structures [15].

The decision of strict non-stationary Maxwell's equations where the derivative of two-dimensional transverse electric field (TE) wave equation for a linear isotropic material polarized along the direction of movement in free field can be written as [16]:

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x}\right), \quad (1)$$

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu_0}\frac{\partial E_y}{\partial z}, \quad (2)$$

$$\frac{\partial H_z}{\partial t} = -\frac{1}{\mu_0}\frac{\partial E_y}{\partial x}. \quad (3)$$

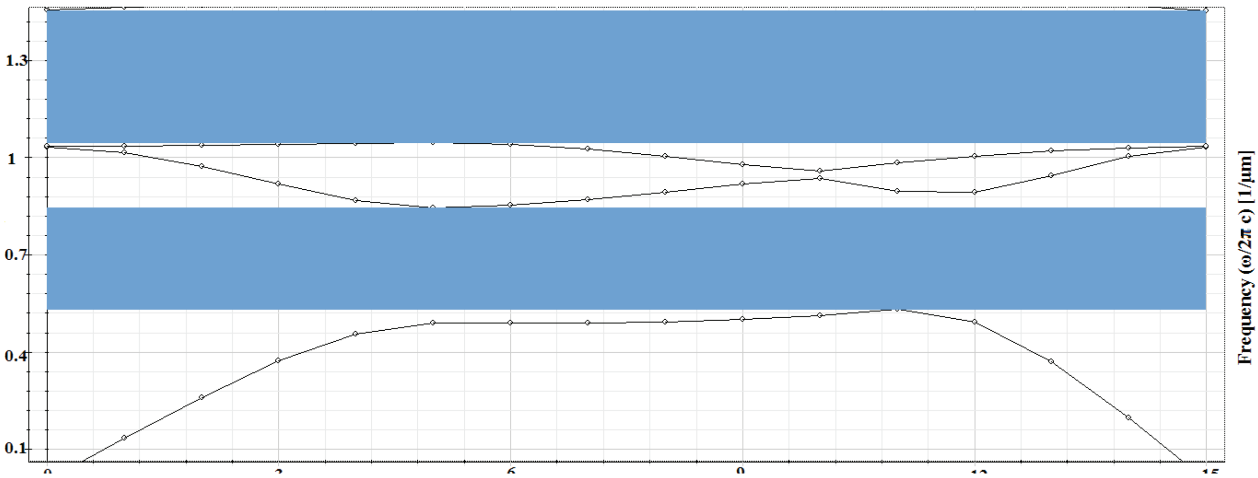


Fig. 2. Band gaps a for T-shape photonic crystal waveguide for the TE mode.

Where $\varepsilon = \varepsilon_0 \varepsilon_R$ are the dielectric permittivity and the magnetic permeability in vacuum.

These equations are called grid technique Yi or Yi algorithm and can be discrete in free-space and time. The spatial dimensions of the equations 1-3 are divided into discrete two-dimensional grid with a time differential step in E-polarization x-z coordinate system [15] [17],

$$H_x^{n+1/2}(i,k+1/2) = H_x^{n-1/2}(i,k+1/2) + \\ +\frac{\Delta t}{\mu_0 \Delta z}\left[E_y^n(i,k+1) - E_y^n(i,k)\right], \quad (4)$$

$$H_z^{n+1/2}(i+1/2,k) = H_x^{n-1/2}(i+1/2,k) - \\ -\frac{\Delta t}{\mu_0 \Delta z}\left[E_y^n(i+1,k) - E_y^n(i,k)\right], \quad (5)$$

$$E_y^n(i,k) = E_y^{n-1}(i,k) + \frac{\Delta t}{\varepsilon \Delta z}\begin{bmatrix} H_x^{n-1/2}(i,k+1/2) - \\ -H_x^{n-1/2}(i,k-1/2) \end{bmatrix} - \\ -\frac{\Delta t}{\varepsilon \Delta x}\left[H_z^{n-1/2}(i+1/2,k) - H_z^{n-1/2}(i-1/2,k)\right]. \quad (6)$$

Where n is an index which enumerates the discrete time step; indices i and k take into account the number of spatial steps in x-z plane, respectively; Δx and Δz an interval between the points on the grid along the x and z directions; Δt - the increasing the time step.

Numerical derivative the time step is a proportion to the number of sampling points. The time step in the FDTD method is determined as follows a:

$$\Delta t \le \frac{1}{c\sqrt{\Delta x^{-2} + \Delta z^{-2}}}. \quad (7)$$

Where c – the speed of light.

The photonic crystal with a T-shape defect is a structure with dielectric rods located in the air as a hexagonal lattice with a refractive index n = 8. In all calculations a/r=0.25 is selected, where a –the lattice constant; r – the radius of rods.

The photonic band gaps for the electrical component (TE polarization) in the two-dimensional photonic crystal were calculated by the plane wave expansion method PWE.

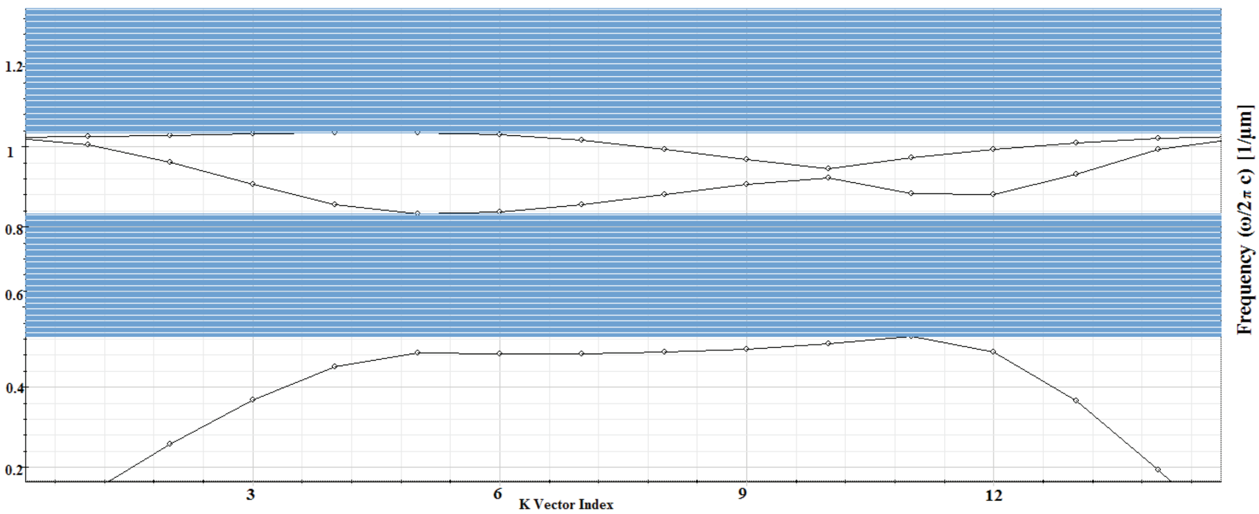


Fig. 3. Band gaps for linear photonic crystal waveguide for the TE mode.

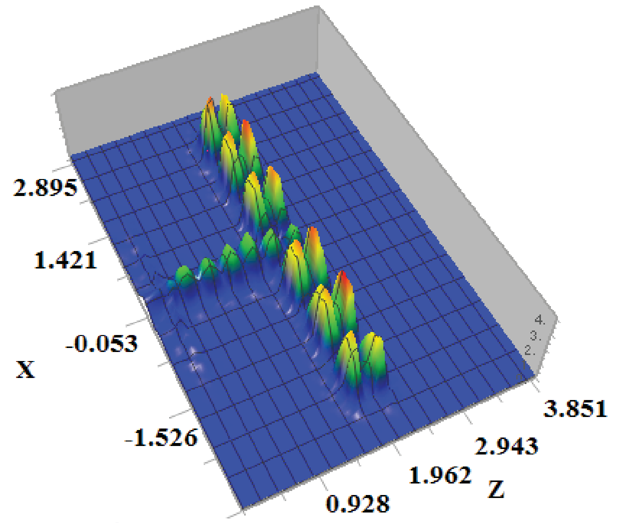


Fig. 4. The field distribution of TE wave in T-shape defect in photonic crystal.

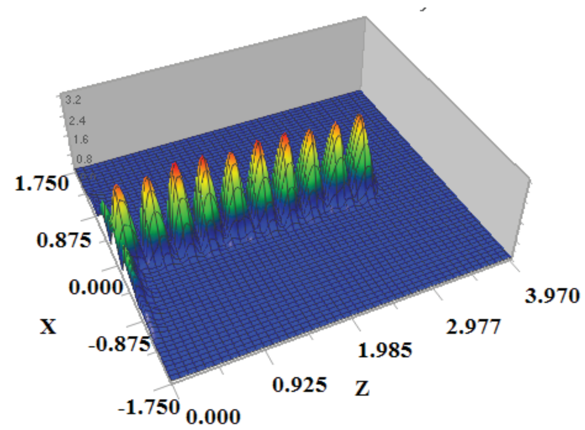


Fig. 5. The field distribution of TE wave in the photonic crystal with linear defect.

The band gapes of the photonic crystal (Figure 2) are located within the range of 0.530-0.840 μm and 1.040-1.450 μm for the incident wave $\lambda = 0.533$ μm.

The photonic crystal with a linear defect also represented the structure located in the air dielectric rods which have a hexagonal lattice with a refractive index n = 6.85. In all calculations a/r=0.3 is selected, where a –the lattice constant; r – the radius of rods.

Band gaps of the photonic crystal (Figure 3) were located within the range of 0.515-0.828 μm and 1.027-1.440 μm for the incident wave $\lambda = 0.533$ μm.

We have modeled a situation where the radiation is run into the photonic crystal the wavelength of which corresponds to the band gap of the photonic crystal. As a result, the field distribution (Fig. 4-5) is obtained. We can see from the calculation results, field concentration takes place within the photonic crystal defect. Since the defect is surrounded by a photonic crystal with a band gape, which corresponds to a wavelength of radiation.

As can be seen from the results of calculations (Figures 4 and 5), the field concentration takes place within the defect photonic crystal, and a photonic crystal in the field cannot extend. The concentrated field occupies the central part of the defect; this area has fairly clear boundaries due to the reflection of radiation from a photonic crystal with a frequency corresponding to the band gape.

Due to the concentration of the field in the center of the defect gradient force, or in the microwave band, is called force Miller, allows to keep the micro and nano particles including atoms and ions in the middle of the defect. Considering near the border of the defect work Casimir-Polder forces [18] the gradient force keeps the center of the defect and does not allow nanoparticles to approach the boundary of the defect.

Conclusion

From the results presented in this article, the features of a qualitative description of the field defect in the photonic crystal are observed. Since the field which accumulates in the defect, as in the resonator has a spatial intensity distribution with a maximum in the central part of the defect and the minimum value on the defect borders. This field it is strongly non-uniform spatial intensity distribution, provides a gradient force that can have an impact at the micro and nano particles from the field. Of course the smaller the size of the particle and its polarizability is smaller, the bigger intensity is necessary for its holding. In these paper preliminary numerical calculations of the field defects are made in the photonic crystals. The localization of the field inside the photonic crystals with different defects that it allows to use the gradient force to hold the nano particles in the defects of photonic crystals has been shown. This gradient force can be used to hold the cooled atoms or ions within the defects.

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