Quantum Electronics **30** (9) 843 – 846 (2000)

PACS numbers: 32.80.Pj; 42.70.Mp
DOI: 10.1070/QE2000v030n09ABEH001816

Laser guiding of cold atoms in photonic crystals

A V Tarasishin, A M Zheltikov, S A Magnitskii, V A Shuvaev

Abstract. The possibility of using photonic crystals with a lattice defect for the laser guiding of cold atoms is analysed. We have found a configuration of a photonic-crystal lattice and a defect ensuring the distribution of a potential in the defect mode of the photonic crystal allowing the guiding of cold atoms along the defect due to the dipole force acting on atoms. Based on quantitative estimates, we have demonstrated that photonic crystals with a lattice defect permit the guiding of atoms with much higher transverse temperatures and a much higher transverse localisation degree than in the case of hollow-core fibres.

1. Introduction

In recent years, much interest has been expressed in the properties of photonic crystals [1 – 3]. The existence of photonic band gaps (PBGs) in the dispersion relation of such structures and the possibility to localise the electromagnetic field are among the most important properties of photonic crystals. These and many other remarkable properties of PBG structures open up new ways for the solution of many fundamental problems of laser physics and nonlinear optics and offer much promise for numerous applications associated with the creation of optical devices for the formation of ultrashort laser pulses [4] and the control of parameters of such pulses [5], as well as for the development of optical switches [6, 7] and delay lines [8], filters [9], ultrarefractive prisms [9, 10], pulse compressors [11], and elements of near-field microscopy [12].

In this paper, we will consider the possibility of using photonic crystals with a lattice defect for the laser guiding of cold atoms. With an appropriate configuration of the photonic-crystal lattice and the defect, a potential permitting the laser guiding of cold atoms due to the dipole force acting on atoms can be constructed.

The main advantages of the proposed method of laser guiding are associated with a high localisation degree of atoms, the possibility of guiding atoms with much higher transverse temperatures than in the case of hollow-core fibres, and suppression of spontaneous emission at the wavelengths falling within the photonic band gap.

A V Tarasishin, S A Magnitskii, V A Shuvaev International Teaching and Research Laser Center at the M V Lomonosov Moscow State University, Vorob'evy gory, 119899 Moscow, Russia;
e-mail: taras@mem3.phys.msu.su
A M Zheltikov Department of Physics, M V Lomonosov Moscow State University, Vorob'evy gory, 119899 Moscow, Russia

Received 31 March 2000
Kvantovaya Elektronika **30** (9) 843 – 846 (2000)
Translated by A M Zheltikov; edited by M N Sapozhnikov

2. The procedure of simulations

To investigate the field distribution in a PBG structure, we employed a numerical procedure based on direct integration of the Maxwell equations using the finite-difference time-domain (FDTD) technique [13]. Recently, this approach has gained a wide recognition from the photonic-crystal community. In particular, this method was successfully applied for the analysis of optical switching [7] and formation of ultrashort light pulses in one-dimensional PBG structures [4, 11], as well as for the investigation of the propagation and localisation of light in two-dimensional photonic crystals [12, 14]. The procedure of simulation of the field distribution in two-dimensional photonic crystals with a lattice defect based on direct integration of the Maxwell equations using the FDTD technique was discussed in detail in [15].

The solution of initial and initial–boundary wave problems for areas with finite sizes (e.g., photonic crystals with finite sizes) encounters difficulties associated with the reflection of an electromagnetic wave from the boundary of the simulation area. The resulting mirror-reflected wave propagates in the area of simulations in backward direction, distorting the physical distribution of the electromagnetic field. Therefore, the boundary conditions in such a situation should be formulated in such a way as to ensure the absorption of a light wave reaching the boundary with no backward reflection of this wave.

Unfortunately, no ideally absorbing boundary conditions can be found for two- and three-dimensional problems in a reasonably simple form. In our simulations, we employed absorbing boundary conditions of the second kind [16], which considerably reduced the influence of reflection from artificial boundaries on the accuracy of numerical simulations:

$$\left(\frac{\partial^2}{\partial y \partial t} - \frac{\partial^2}{\partial t^2} + \frac{1}{2}\frac{\partial^2}{\partial x^2}\right) E_z(\boldsymbol{r}, t)\Big|_{y=-L/2, L/2} = 0, \qquad (1)$$

where L is the length of the simulation area along the y-coordinate, which coincides with the direction of propagation of laser radiation. The electric field in the incident wave is polarised along the z axis, which is perpendicular to the xy plane of symmetry of the crystal. The crystal has a size on the order of $10a$ along the y axis, where a is the lattice period. A linear defect was introduced into the lattice of the photonic crystal in order to channel laser radiation with a frequency lying within the photonic band gap along the y axis. Since we assume that the crystal is infinite along the x axis, periodic boundary conditions

$$H_x\left(-\frac{\Lambda}{2}, y, z, t\right) = H_x\left(\frac{\Lambda}{2}, y, z, t\right),$$

$$H_y\left(-\frac{\Lambda}{2}, y, z, t\right) = H_y\left(\frac{\Lambda}{2}, y, z, t\right), \qquad (2)$$

$$E_z\left(-\frac{\Lambda}{2}, y, z, t\right) = E_z\left(\frac{\Lambda}{2}, y, z, t\right),$$

where Λ is the period of the resulting superlattice along the x axis, were used jointly with absorbing boundary conditions (1). Since the penetration depth of a light wave in the considered PBG structure within the frequency range corresponding to the photonic band gap is less than or of the order of the period of the photonic-crystal lattice, the values of Λ lying within the range of $(5-10)a$ can be employed to simulate the channelling of electromagnetic radiation along the linear defect.

To test the efficiency of the above-described boundary conditions, we simulated the reflection of tightly focused short-pulse beams. These simulations have demonstrated that the amplitude reflection coefficient for a Gaussian beam with a diameter of the order of its wavelength and an incidence angle of 45° does not exceed 3%, which is consistent with the results of simulations performed in [16] for a plane monochromatic wave.

As an object of simulations, we chose a two-dimensional structure consisting of a variable number of periods (from five to ten) of cylindrical air holes arranged in a triangular lattice in silicon. A potential with an isolated extremum within some area inside the defect should be constructed to trap atoms at the centre of the defect in the considered PBG structure. This problem can be solved if we employ a two-dimensional photonic crystal with a complex geometry of the defect in the crystal lattice shown in Fig. 1. An appropriate distribution of the electromagnetic field in this case can be produced by focusing a laser beam with a cylindrical lens whose axis is parallel to the axes of the holes in the photonic crystal (Fig. 1).

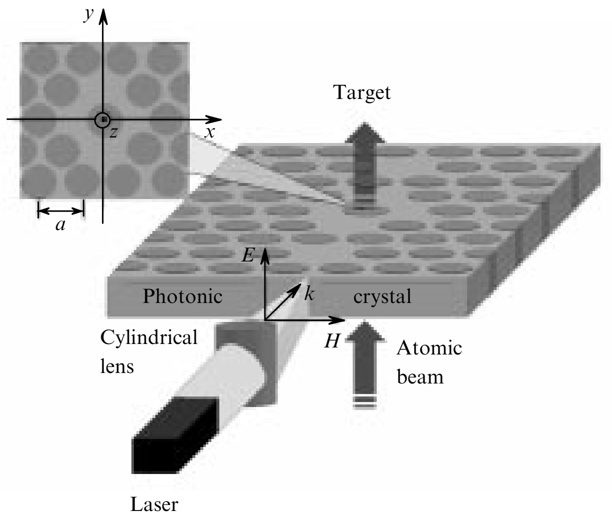

Figure 1. Laser guiding of cold atoms in a defect mode of a two-dimensional photonic crystal. The inset shows the configuration of the photonic-crystal lattice and a defect in this lattice.

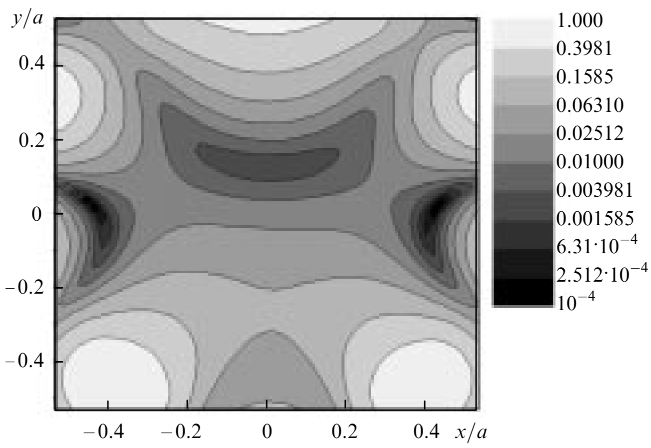

Figure 2. Distribution of the electric field intensity in the two-dimensional photonic crystal with a lattice defect. The levels of grey scale represent the mean values of the electric field squared normalised to their maximum.

3. Results and discussion

The calculated distribution of the electric field intensity in the defect mode of the considered photonic crystal is presented in Fig. 2. One can see from this map, that with a defect introduced into a photonic-crystal lattice, the electric field in the defect mode decreases by more than five orders of magnitude within a spatial scale less than the optical wavelength. Physically, the appearance of such steep field gradients in a PBG structure with a complex geometry of the lattice defect shown in Fig. 1 is due to the following factors.

The field of an electromagnetic wave whose frequency lies within the photonic band gap is localised in the defect mode of the photonic crystal within a spatial area with a size of the order of optical wavelength (see also [14, 15]). At the same time, the electromagnetic field is expelled from the central hole of the defect region of the photonic crystal to the area with a higher refractive index (see the inset in Fig. 1). The characteristic spatial scale of the field gradient arising at the interface between the area with a high dielectric constant ε and the region with a low refractive index (air in the case under study) can be estimated as $\lambda/[2\pi(\varepsilon-1)^{1/2}]$, where λ is the wavelength of the light field. This estimate provides a qualitative explanation of steep gradients of electromagnetic fields arising in the considered structure.

Let us estimate the characteristic parameters of the potential created in such a structure in the case of a two-level atom irradiated with a controlling laser light whose frequency is blue-detuned from the atomic resonant transition. The depth of such a potential well can be estimated from the expression [17]:

$$U = \hbar\Omega \ln\left[1 + \frac{I}{I_{\text{sat}}}\frac{\gamma_{\text{n}}^2/4}{\Omega^2 + \gamma_{\text{n}}^2/4}\right], \qquad (3)$$

where I is the intensity of the laser beam at the periphery of the defect (the maximum intensity of laser radiation); I_{sat} is the saturation intensity of the considered atomic transition; $\Omega = \omega - \omega_0 - kv_z$ is the detuning from the atomic resonance (blue detuning in the case under study), and γ_n is the natural line width.

In the case of the $6^2S_{1/2} - 6^2P_{3/2}$ transition of cesium atoms (with a wavelength of 852 nm), atoms can be guided in the considered structure with quasi-cw Ti: sapphire laser radiation with a wavelength of 852 nm and a power below 1 W. Suppose that, in order to guide atoms within the guidance length of 1 cm, we focus a laser beam blue-detuned from the considered atomic transition by 4 GHz with a cylindrical lens (Fig. 1) into a $10^{-4} \times 1$-cm spot. Then, we arrive at $I = 10^4$ W cm^{-2} for the above-specified parameters of laser radiation. Taking into account that $I_{sat} = 1.06$ mW cm^{-2} for the considered transitions in cesium atoms, we find that $I/I_{sat} = 10^7$ for the chosen transition.

Thus, the light field intensity distribution presented in Fig. 2 allows the guiding of cold atoms, since it traps a two-level atom in two dimensions. The presence of the atomic velocity component along the z axis in such a situation leads to the drift of atoms in this direction.

The potential depth (3) reaches its maximum for $\Omega \approx 1.6 \times 10^3 \gamma_n/2$. Since $\gamma_n = 5$ MHz for the considered transition in cesium, we can estimate the potential depth as $U \approx 6.35 \times 10^{-25}$ J, and the transverse temperature of atoms is $T = U/k = 460$ mK, which corresponds to the maximum transverse velocity of atoms equal to $v_m = (2U/m)^{1/2} = 2.3$ m s^{-1}.

The estimates presented above allow us to conclude that photonic crystals with a lattice defect can be used to guide atoms with much higher transverse temperatures than the temperatures typical of atoms guided by hollow-core fibres [18, 19]. Yet another important advantage of using photonic crystals for the laser guiding of atoms is associated with the possibility to reduce the probability of spontaneous emission of guided atoms within the range of wavelengths falling within the photonic band gap.

With the considered geometry, where atoms are guided by a cylindrically focused laser light (see Fig. 1), atomic dipoles are oriented in the direction perpendicular to the xy plane of periodicity of the photonic crystal. Since the frequency of the considered atomic transition lies in the photonic band gap in the case under study, the density of states of the electromagnetic field polarised along the z axis is equal to zero. In accordance with the Fermi golden rule, the lifetime of excited-state atoms should increase under these conditions.

This effect allows one to considerably increase the time of trapping of atoms around the minimum of the potential well in a defect mode of a photonic crystal, providing favourable conditions for the investigation of quantum-electrodynamic effects accompanying the interaction of an atom with electromagnetic radiation.

Finally, we should note that the localisation degree of atoms in defect modes of photonic crystals is much higher than the localisation degree of atoms in hollow-core fibres, whose characteristic diameters are usually of the order of several tens of microns. On the other hand, we have to admit that the proposed approach to the laser guiding of cold atoms is more difficult to implement experimentally as compared with the method of hollow-core fibres, and the guidance lengths attainable with the proposed technique are typically less than the guidance lengths characteristic of hollow-core fibres.

4. Conclusions

Thus, photonic crystals with a lattice defect can be employed for the laser guiding of cold atoms. Direct integration of the Maxwell equations using the finite-difference time-domain technique shows that such structures allow the localisation of electromagnetic field on a subwavelength spatial scale.

Analysis performed in this paper allowed us to find the configuration of a photonic-crystal lattice and a defect producing a potential that permits the guiding of cold atoms along the defect of the photonic crystal due to the dipole force acting on atoms and the drift of atoms along the lines of constant amplitude and constant phase of the field.

Photonic crystals with a lattice defect can be employed to guide atoms with much higher transverse temperatures and can provide much higher transverse localisation degrees of atoms as compared with hollow-core fibres. Along with the transport of atoms and filtering of cold atoms in their velocities, photonic-crystal atom guides introduced in this paper seem to hold much promise for the investigation of quantum-electrodynamic aspects of the interaction of atoms with microcavity modes and the implementation of quantum computations.

Acknowledgements. One of us (A M Zh) is grateful to D Meschede and V Gomer for useful discussions. This study was supported in part by the President of Russian Federation (Grant No. 00-15-99304) and the Russian Foundation for Basic Research (Grant No. 00-02-17567).

References

1. Yablonovitch E *J. Opt. Soc. Am. B* **10** 283 (1993)
2. Joannopoulos J, Meade R, Winn J *Photonic Crystals: Molding the Flow of Light* (Princeton: Princeton Univ., 1995)
3. Soukoulis C *Photonic Band Gap Materials* (Dordrecht: Kluwer Academic, 1996)
4. Zheltikov A M, Koroteev N I, Magnitskii S A, Tarasishin A V *Kvantovaya Elektron. (Moscow)* **25** 885 (1998) [*Quantum Electron.* **28** 861 (1998)]
5. Zheltikov A M, Koroteev N I, Magnitskii S A, Tarasishin A V *Izv. Ross. Akad. Nauk Ser. Fiz.* **65** 717 (1999)
6. Scalora M, Dowling J P, Bowden C M, Bloemer M J *Phys. Rev. Lett.* **73** 1368 (1994)
7. Tran P *Opt. Lett.* **21** 1138 (1996); Scholz S, Hess O, Ruhle R *Opt. Express* **3** 29 (1998)
8. Scalora M, Flynn R J, Reinhardt S B, Fork R L, Bloemer M J, Tocci M D, Bowden C M, Ledbetter H, Bendickson J, Dowling J P, Leavitt R P *Phys. Rev. E* **54** R1078 (1996)
9. Zheltikov A M, Naumov A N, Barker P, Miles R B *Opt. Spectrosc.* **89** 309 (2000)
10. Lin S-Y, Hietala V M, Wang L, Jones E D *Opt. Lett.* **21** 1771 (1996)
11. Koroteev N I, Magnitskii S A, Tarasishin A V, Zheltikov A M *Opt. Commun.* **152** 191 (1999)
12. Magnitskii S A, Tarasishin A V, Zheltikov A M *Appl. Phys. B* **69** 497 (1999)
13. Taflove A *Computational Electrodynamics: The Finite-Difference Time-Domain Method* (Norwood, MA: Artech House, 1995)
14. Zheltikov A M, Magnitskii S A, Tarasishin A V *Pis'ma Zh. Eksp. Teor. Fiz.* **70** 323 (1999) [*JETP Lett.* **70** 323 (1999)]
15. Zheltikov A M, Magnitskii S A, Tarasishin A V *Zh. Eksp. Teor. Fiz.* **118**, 234 (2000) [*JETP* **90** 600 (2000)]
16. Engquist B, Majda A *Math. Comput.* **31** 629 (1977)

17. Ashkin A *Phys. Rev. Lett*. **40** 729 (1978)
18. Ol'shanii M A, Ovchinnikov Yu B, Letokhov V S *Opt. Commun.* **98** 77 (1993)
19. Renn M J, Montgomery D, Vdovin O, Andreson D Z, Wieman C E, Cornell E A *Phys. Rev. Lett*. **75** 3253 (1995)